NASA CR-135354

QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE)

BALL SPLINE PITCH-CHANGE MECHANISM WHIRLIGIG TEST REPORT

(NASA-CR-135354) QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE) BALL SPLINE PITCH-CHANGE MECHANISM WHIRLIGIG TEST REPORT (General Electric Co.) 64 p HC A04/MF A01 CSCL 21E G3/07 N80-15115 Unclas 33498

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1.0 SUMMARY

The ball spline actuation system, shown in Figure 1 and completely described in NASA report CR-134873, is being developed by General Electric. A hydraulic motor located on the fan centerline drives a ball screw actuator through a differential gear and no-back. Linear motion of the ball nut of the ball screw causes the translating sleeve (middle member) of a ball spline to move in a fore or aft direction. The ball spline is a double-acting member with helical ball tracks between the translating sleeve and inner member and straight ball tracks between the sleeve and outer ball spline member. The inner member is attached to the aft ring gear while the outer member is attached to the forward ring gears in tangentially opposite directions. The ring gears, in turn, are mated to 18 pinion gears that are splined to the corresponding fan-blade trunnion. Gear ratio between the hydraulic motor and the fan blade is 479/1. Two LVDT's driven by the hydraulic motor provide blade-angle feedback to the engine digital control system.

The GE ball spline variable pitch (VP) actuation system successfully completed all planned whirligig tests. All hardware was in very good condition after the tests.

Total fan blade angle range is 129° from the forward to the aft stop of the actuator. A static hysteresis of 3° was measured when changing the direction of blade actuation at zero fan speed. At 95% fan speed (3070 rpm), the dynamic hysteresis was within 0°10' when setting the blade from opposite directions. Up to 102% fan speed (3400 rpm), the minimum observed blade angle change was about 0.2 - 0.3 degrees and the required hydraulic pressure was about 1700 psi. After initial slippage and subsequent reshimming, the no-back held up to 102% fan speed.

The VP actuation system successfully completed a cyclic endurance test with fifty simulated flight mission cycles at actuation rates up to 125 degrees per second at up to 102% fan speed (3400 rpm). The GE VP actuation system operated successfully with the UTW engine "breadboard" digital control.

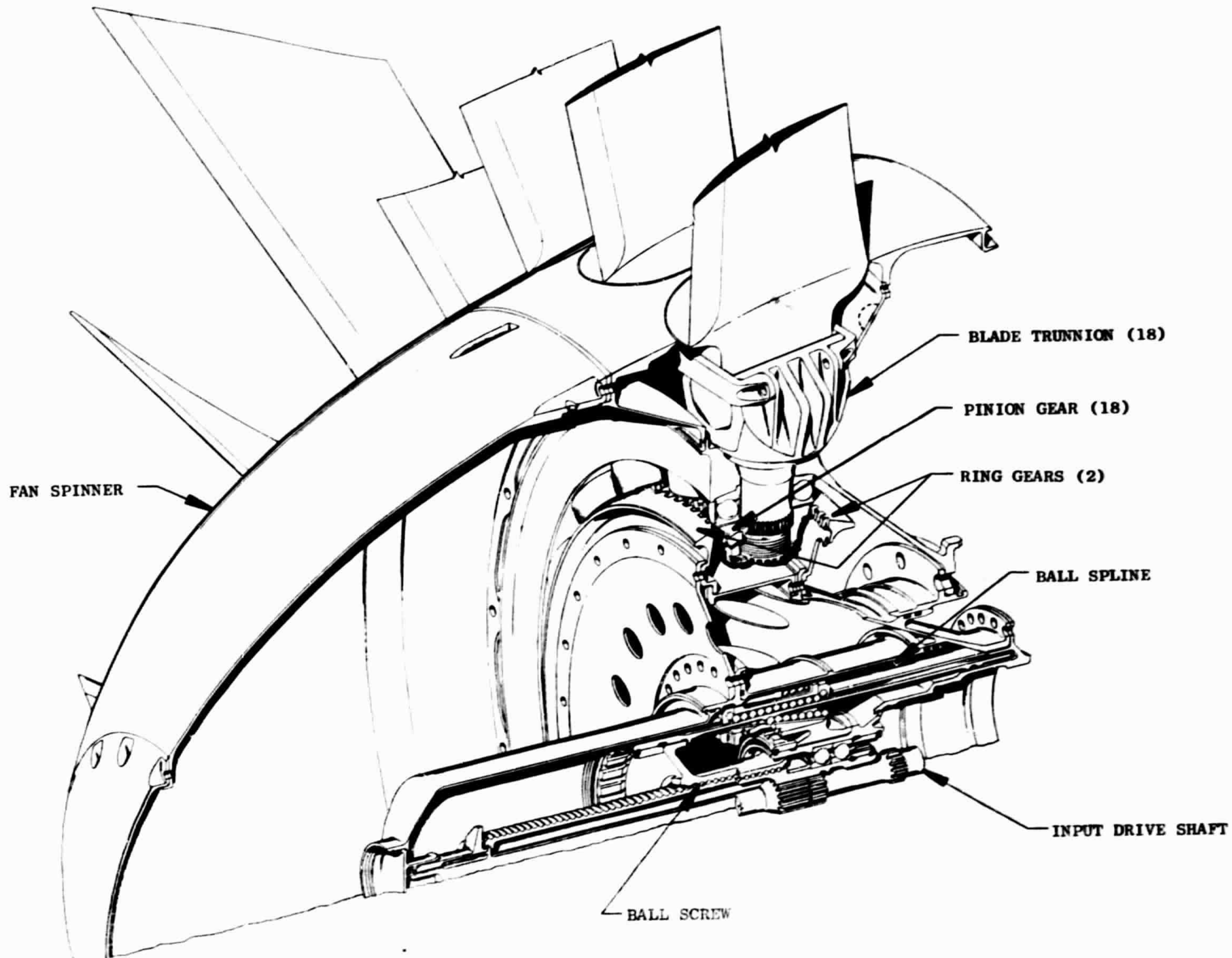

Figure 1. GE Ball Spline Actuator System.

2.0 INTRODUCTION

The Quiet Clean Short-Haul Experimental Engine (QCSEE) Program provides for the design, fabrication, and testing of two experimental, high-bypass, geared-turbofan engines and propulsion systems for short-haul, passenger aircraft. The under-the-wing (UTW) propulsion system, being developed as a part of this program, is a low tip-speed, low pressure ratio turbofan engine that features a variable-pitch fan.

Two variable-pitch fan actuation systems were selected for engine test in the UTW experimental engine program. A cam/harmonic-drive system is being developed by the Hamilton Standard Division of United Technology Corporation under subcontract to the General Electric Company. The second system, a ball spline actuation system, is being developed by General Electric.

Final design of the General Electric ball spline actuation system is presented in NASA CR-134873. The corresponding UTW Engine Final Design Report is NASA CR-134847.

This report presents the results of the whirligig testing of the General Electric variable-pitch fan system which was completed during the months of March and April of 1976. This test was conducted to ensure design and structural adequacy before UTW engine testing.

In the whirligig tests, the facility drive shaft is forward of the VP actuator and is mounted directly to the forward flange of the fan disk, which is opposite to the normal rear drive in the UTW Engine. Dummy blades were used in the whirligig to simulate the anticipated aerodynamic and centrifugal loads of the UTW Engine composite fan blades. Tests were conducted with a slave control system at slow actuation rates and with the UTW Engine "breadboard" digital control at fast actuation rates.

The GE ball spline actuation system was subsequently installed in the UTW Engine build 2 with the composite nacelle, and tests were initiated in September 1977.

3.0 TEST DESCRIPTION

3.1 TEST HARDWARE DESCRIPTION

The General Electric ball spline actuator system tested is shown in Figures 1 and 2. The actuator functions in the following manner.

Pinion bevel gears attached to each of the 18 fan-blade trunnions are rotated by the motion of two ring bevel gears. The pinion bevel gears are attached to the trunnions by accurately positioned fine pitch splines which allow for proper synchronizing with the two ring bevel gears. The fine pitch splines also permit reindexing of the blades to vary the open and closed blade-angle limits for engine thrust reversal both through stall and through flat pitch. Use of two ring gears permits load sharing and adds redundancy to the system. An axial tie member in the area of the pinions prevents separation of the two ring gears. Overall gear ratio of the pinion bevel-gear/ring-gear mesh is designed to achieve the maximum gear capacity within the space available between any two blades. A shim is provided to ensure proper tooth meshing.

The ring gears are rotated by a ball spline driven by a rigid translating sleeve. The forward ring gear is driven by the outer (straight) portion of the ball spline while the aft ring gear is driven by the inner (helical) portion of the ball spline. As shown in Figure 2, both ring gears are easily removed at their bolted flange joints for modular assembly and disassembly of the actuator.

The rigid translating sleeve of the ball spline is driven by a ball screw through a stroke of 15.49 cm (6.10 in.) to achieve a blade rotation of 135°. The balls of the ball spline ride in a continuous path made up of a loaded track and a return guide. The return guides are tubes located out of the load zone. Loaded tracks and return guides are connected by end return caps. These end caps permit easy replacement of the balls during servicing.

Helical ball tracks between the inner and middle members of the ball spline generate a maximum axial load during normal operation of approximately 108.5 kN (24,398 lbf). These axial loads are reacted from the middle member into the ball screw through a ball nut. Ball screw thrust loads are transmitted back into the inner member through a set of precision-ground M50 duplex thrust ball bearings. Thus, all high actuator axial loads are close looped on a small diameter within the actuator. This close coupling of high axial loads was instrumental in achieving a low weight for a flight system.

As shown in Figure 2, power to drive the ball screw is provided by a hydraulic motor acting through a gear differential. A ball/ramp-type no-back is included between the differential gear and the ball screw to allow torque to be transmitted only in one direction. Axial stops at each end of the ball screw (Figure 2) limit actuator travel.

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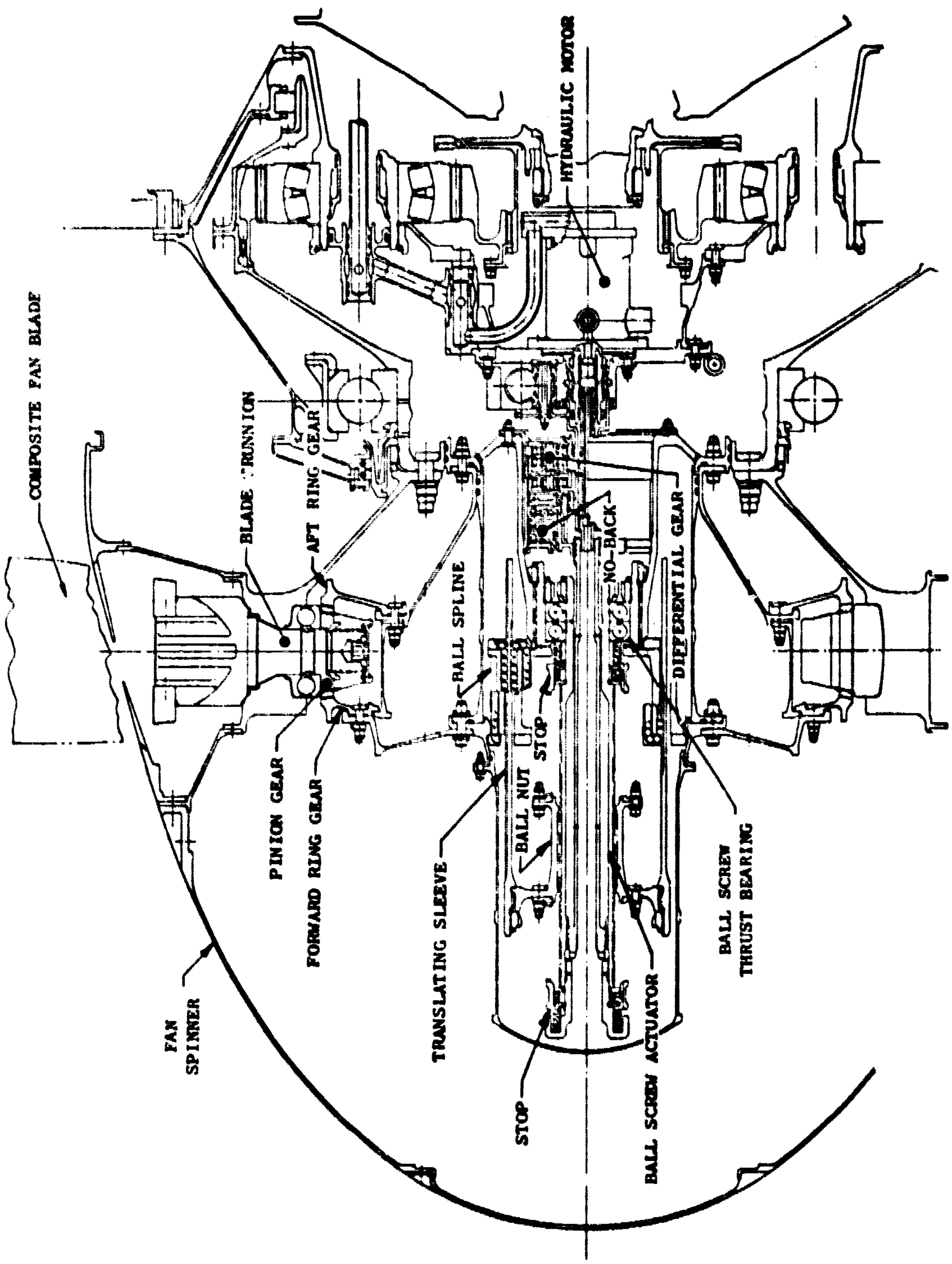

Figure 2. General Electric Ball Spline Actuation System.

3.2 TEST FACILITY DESCRIPTION

Figure 3 shows the facility layout utilized to whirligig test the GE variable-pitch mechanism.

A 2982.8 kW (4000 hp) drive motor is provided; it drives through a dynamic coupling to a speed-increaser gearbox which terminates in a drive-spindle assembly to which the component test vehicle is mounted in a cantilever manner. The facility also features a blading shroud which reduces blade pumping and minimizes the power required to drive the test vehicle.

The component test vehicle is shown in Figure 4. The variable-pitch actuator is mounted directly to the facility spindle shaft by the forward flange of the fan disk. On the UTW engine the fan disk is driven through the main reduction gear by the aft flange of the fan disk. By driving through the forward flange on the whirligig test the stationary components (feedback mechanism and hydraulic motor) which are mounted to a stationary frame are easily accessible. This mounting arrangement does not affect the functional characteristics of the actuator. Mounted to the stationary frame is an oil retainer which collects the lubricating oil from the actuator.

The fan blades are simulated by using dummy blades. These type blades do not pump air as the actual blades would but do produce the blade twisting moments of the actual blades. Figure 1.0 in Appendix A shows the characteristics of the dummy blades versus the UTW fan blade net twisting moments.

The hydraulic control system schematic is shown in Figure 5. A 27.6-MN/m^2 (4000-psi) Denison variable-volume pump with flow capacity of 1261.8 cm^3/sec (20 gpm) was used. During the later phases of the testing it was found that an accumulator had to be added to keep the hydraulic motor supply pressure from reducing during rapid blade transients. The engine servovalve was used during all testing. The servovalve directed hydraulic fluid to the open or closed port of the variable-pitch, hydraulic motor. The feedback LVDT's provided the position signal to the "breadboard" digital control. The "breadboard" digital control supplied the command signal to the servovalve. During the early test phase a slave hydraulic control system was used.

Lube oil was supplied from a facility lube cart which furnished approximately 47.3 cm^3/sec (0.75 gpm) at 310.3 kN/m^2 (45 psig).

Figure 6 shows the test cell control console with digital control modules mounted. In addition to panel instrumentation, an eight-channel recorder was utilized to record transient data. A list of instrumentation used in the whirligig test is included in Section IV-5 of Appendix A.

3.3 TEST PROCEDURE

The General Electric test project sheet (TPS) used for this test is included in Appendix A of this report. Below is a summary of what is contained in this TPS. Where any procedural deviations were made they are described.

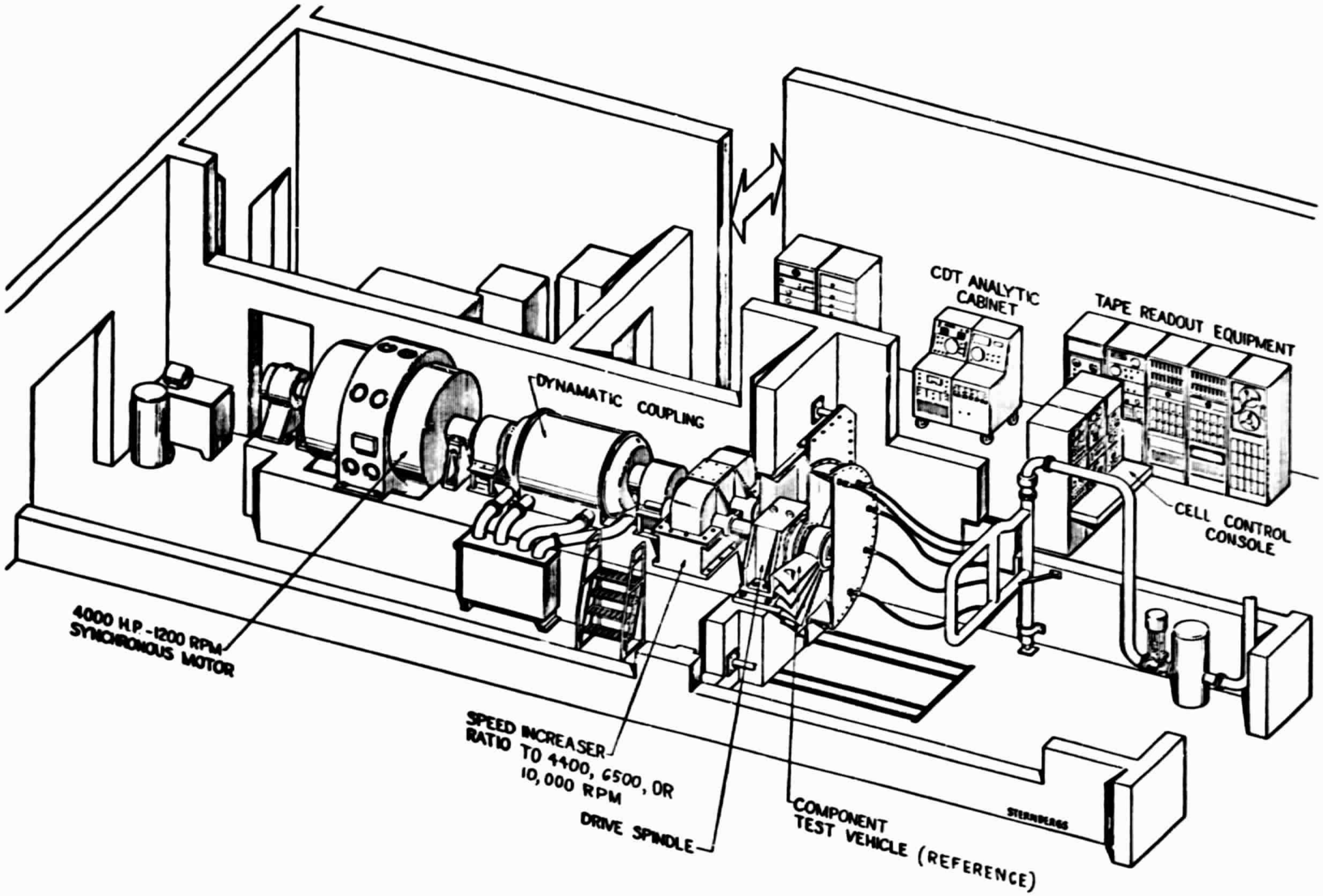

Figure 3. Whirligig Facility, Cell 63.

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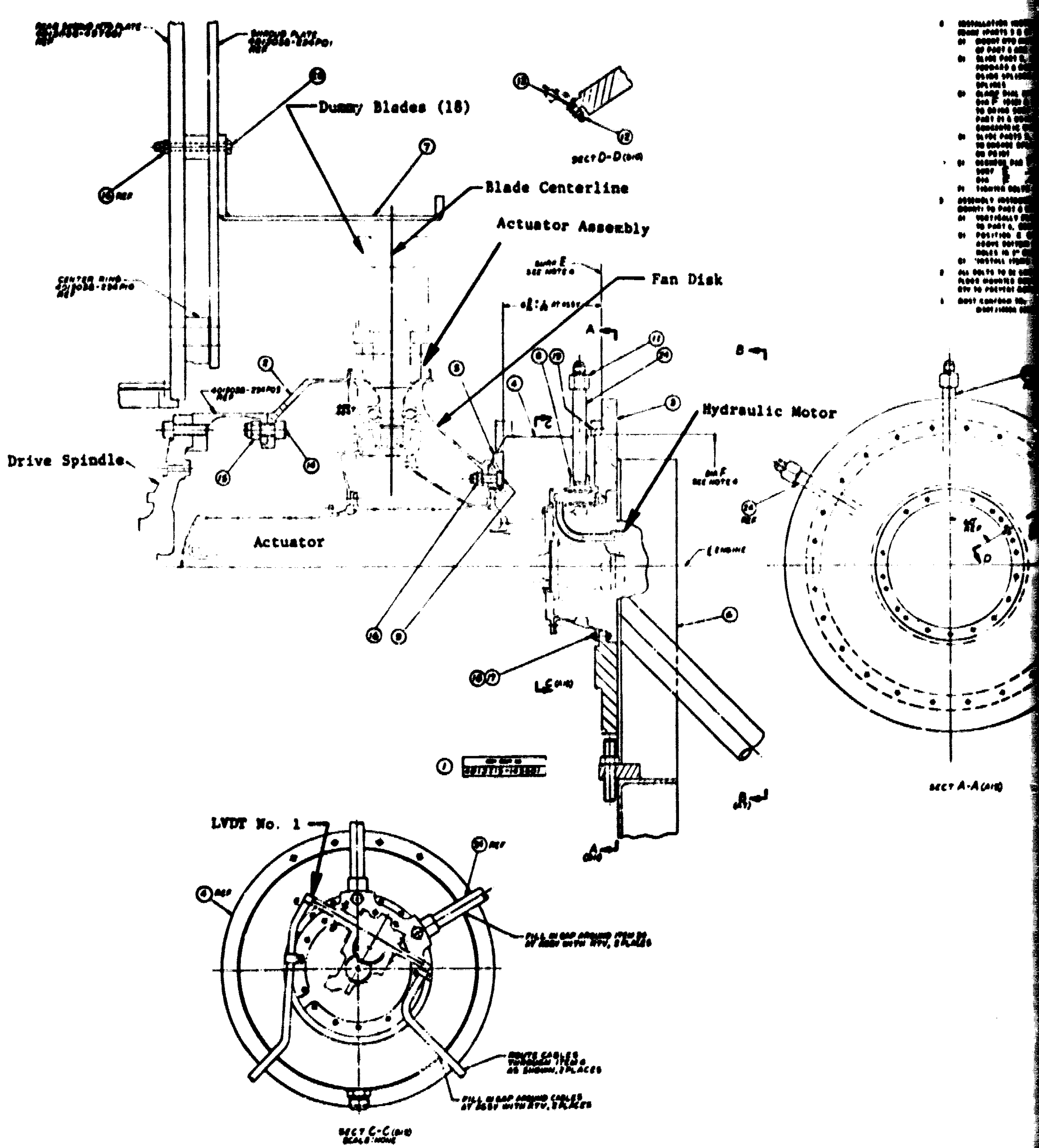

Figure 4. Installation of General Elec

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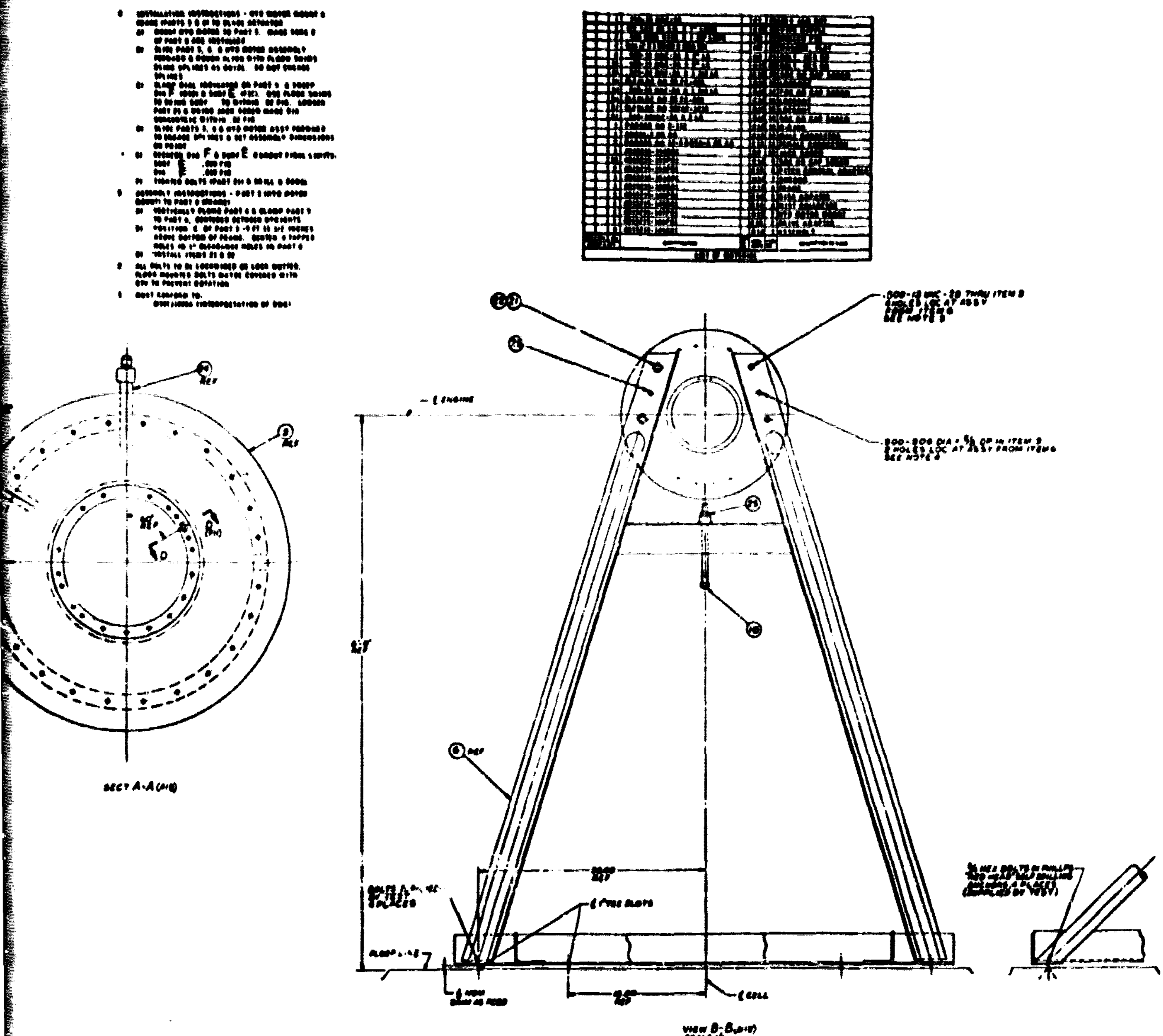

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of General Electric VP in Whirligig Test Cell.

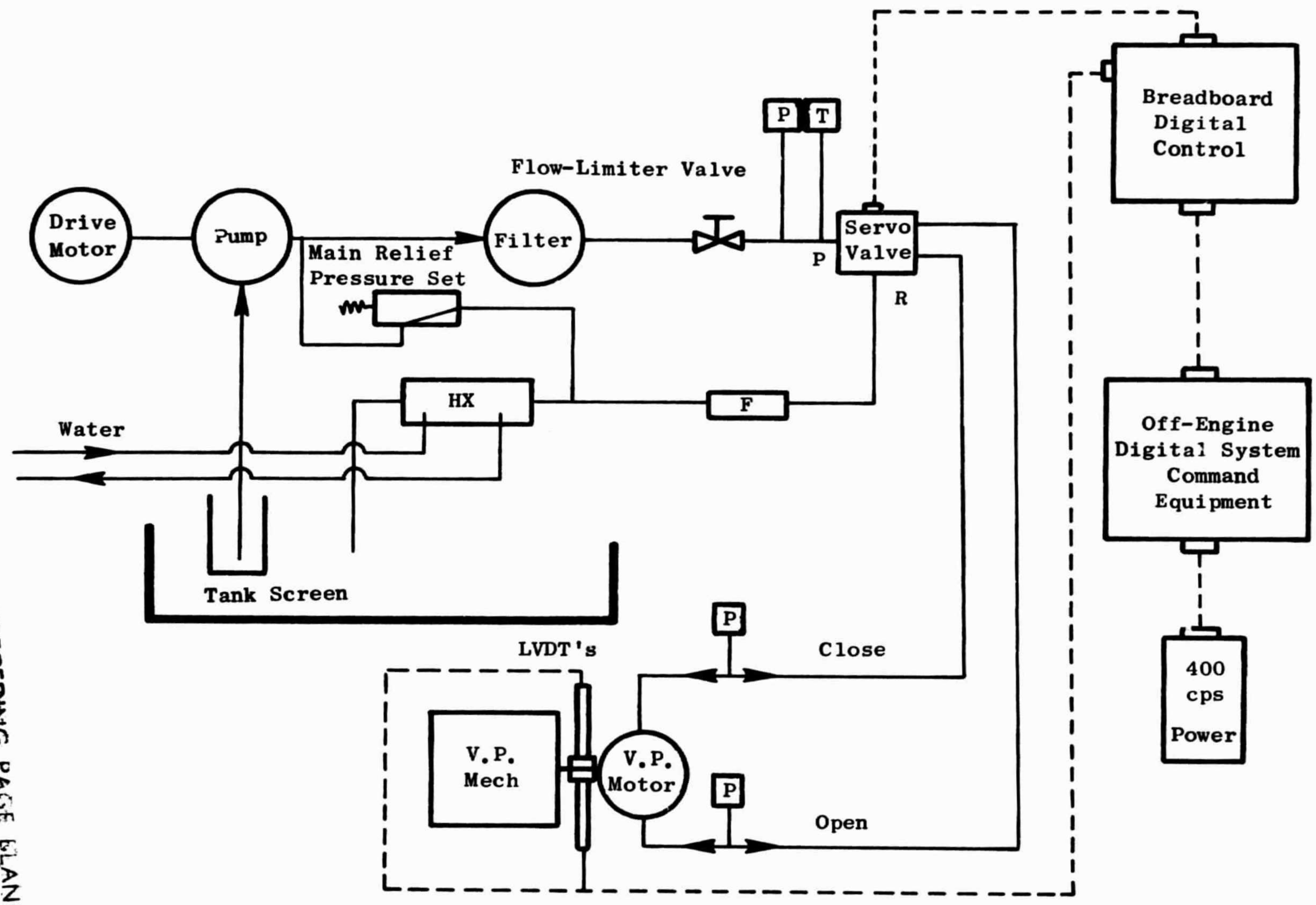

Figure 5. Hydraulic Control-System Schematic.

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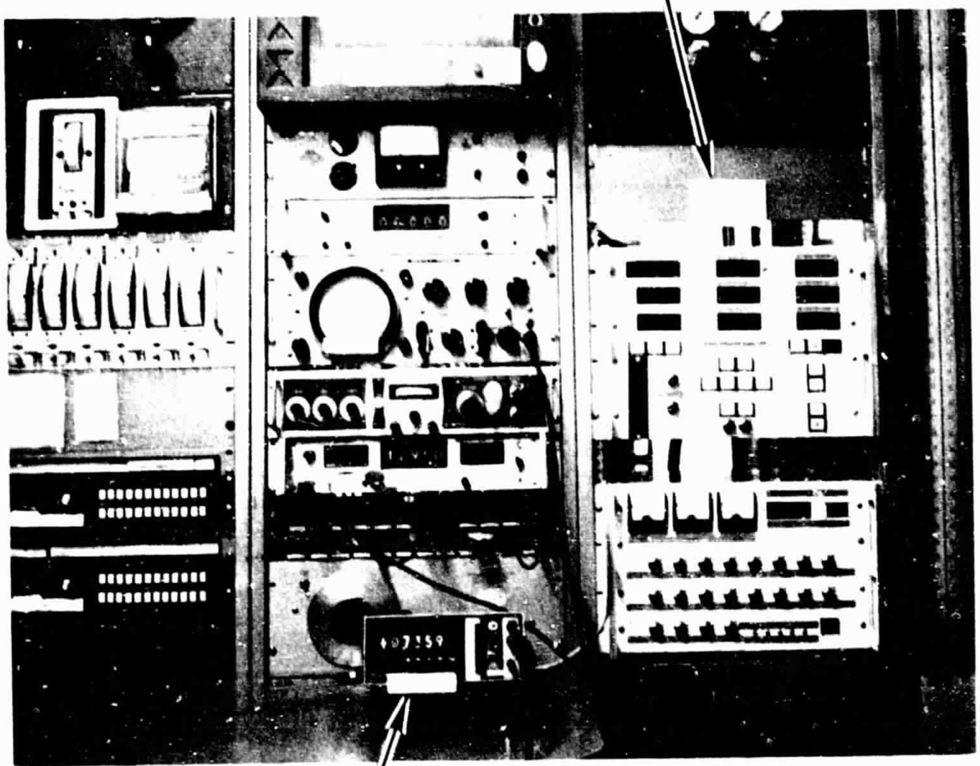
Digital Control



LVDT Readout

Figure 6. Test Cell Control Console.

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3.3.1 Manual Checkout

A manual checkout was completed before the fan rotor was rotated. During this checkout the LVDT readings versus blade angle were recorded to determine blade positioning for the remainder of the test. Actual blade-angle measurements during all testing were obtained by measuring a predetermined blade with a clinometer. A mechanical-drive input with a torque-recording device was used to establish the no-load torque requirements of the actuator; this was recorded in both directions. With the hydraulic-system flow restricted to less than 315.4 cm^3/sec (5 gpm), the actuator was exercised between 13° closed and 115° open.

3.3.2 Low Fan Speed Checkout

It was originally planned to perform all slow-actuation checkouts with a slave hydraulic-control system. (Reference Figure 4.0 of Appendix A.) Problems developed with this slave control system and it was decided to use the "breadboard" digital control for the majority of the test.

The only portion of the test that used the slave control system was the low fan speed (1000 rpm) checkout to check for lubrication leaks and to determine the blade-angle position that required maximum hydraulic motor ΔP (described in paragraph 3.3.3).

3.3.3 Operation Characteristics at Slow Actuation Rates

The next phase of testing included determining the angle where maximum hydraulic motor ΔP was required to move the blades. This was determined at a fan speed of 1000 rpm using the slave control system. A "no-back" holding test was scheduled at 3347 rpm with blades positioned at the angle where maximum holding torque is required.

The hydraulic motor ΔP required to move the blades at the following positions was also determined.

- Blade angle set at maximum load point and actuating ±30°
- Blades set at nominal angle and moving them ±5°
- Blades at nominal angle and moving full open

These tests were performed for a fan speed range of 2500 to 3350 rpm in increments of 200 rpm.

At 3347 fan rpm the actuator was cycled 10 times between 5° open to 5° closed. It was also cycled 15 times ±20° from the angle of maximum load while at a fan speed of 2841 rpm.

3.3.4 Blade Angle Accuracy and "Jogging" Capability

When the flow restricter was removed from the control system, a blade angle setting accuracy test was performed. The blades were set and measured at nominal position. Fan speed was than varied between 1000 and 3347 rpm, the blade angle was reset to nominal, and the blade angle was remeasured at shutdown. The "jogging" capability was also completed during this time. To demonstrate that the blade angle could be "jogged," a system of lights was used to visually determine blade movement while the fan was rotating at speeds between 1000 and 3347 rpm. This proved satisfactory for blade indicated movements down to 1.5°, but below this angle 2400 rpm seemed to be the best speed to see movement.

3.3.5 Cyclic Endurance Test

A fifty-cycle endurance test was completed. The test cycle was revised from the TPS with the concurrence of NASA. The cycle shown in Table I was used and is similar to the cycle used in the whirligig testing of the harmonic-drive/cam actuator.

Table I. Cyclic Endurance Test Cycle.

Step	Fan Speed	Blade Angle	LVDT
1	2500 rpm	+ 10	+0.775
2	2500	- 3	+0.55
3	3408	- 3	+0.55
4	3408	0	+0.635
5	3068	0	+0.635
6	3068	+ 7	+0.735
7	3068	+ 5	+0.666
8	3068	+ 7	+0.735
9	3068	+ 9	+0.761
10	3068	+ 7	+0.70
11	Repeat steps 7 through 10 twenty times		
12	3068	-100	-0.815
13	3408	-100	-0.815
14	2500	-100	-0.815
15	2500	+ 10	+0.775

4.0 TEST RESULTS

4.1 MANUAL CHECKOUT

With the hydraulic motor removed from the actuator, as shown in Figure 7, the actuator was mechanically driven to determine the total blade travel and the static load torque required to drive the actuator.

It takes 177 turns to go from just touching the forward stop to just touching the aft stop. From the nominal position the blades can close 13.75° and open 115.5° for a total blade travel of 129.25°. The results from the static load test are shown in Figure 8. The highest and lowest torque are 4.56 N-m (40.0 lb-in.) and 4.07 N-m (36 lb-in.) respectively. The highest torque occurred in the closing direction. Figure 1.0 of Appendix A defines the opening and closing direction of the fan blades.

The LVDT readings versus blade angle calibration data are shown in Table II and plotted in Figure 9. The data from LVDT identified as No. 1 (see Figure 4) were used in plotting Figure 9. Approximately 3° difference was noted when changing direction of blade actuation without fan rotation (static hysteresis). During running the net twisting torque in forward thrust always tends to close the blades. The calculated mechanical backlash (Reference NASA CR134873) is less than 1°. This is 1/3 of that actually measured. The location of the excessive backlash was not investigated during the whirligig test since during operation it caused no problem and blade angle changes of 0.2° were visually verified (see Section 4.4). Some investigations were done during the time the actuator was mounted in the engine. It was found that the majority of the backlash was associated with the ball spline members.

With the hydraulic motor reinstalled, Figures 10 and 11 show the motor hydraulic pressure ΔP required to move blades the full stroke in both directions. Very slow rates were used during these actuations (1.5°/sec maximum). Table III compares data from mechanical-driven test with data from hydraulic-motor-driven test. The motor torques are obtained from Table IV which is data obtained by mounting a torque-absorbing device and recording the torque at various motor pressures. Motor leakages were also obtained during this test. The maximum leakage of 18.5 cm^3 (0.29 gpm) occurred at 23.4 MN/m^2 (3400 psi) while in the closing direction.

4.2 LOW FAN SPEED CHECKOUT

A low fan speed (1000 rpm) checkout was accomplished to determine low speed characteristics and to perform a leak check on the lube system. MIL-L-23699 (Shell No. 555) lubricant was used for this test and was supplied to the actuator continually at 47.3 to 50.5 cm^3/sec (0.75 to 0.80 gpm) at a pressure of 303 to 317 kN/m^2 (44 to 46 psig) and a temperature of approximately 321.9 K (120° F). The slave lube cart provided a filtration level of 5-10 μm. No lube-system problems occurred during this checkout or during the remainder of the test.

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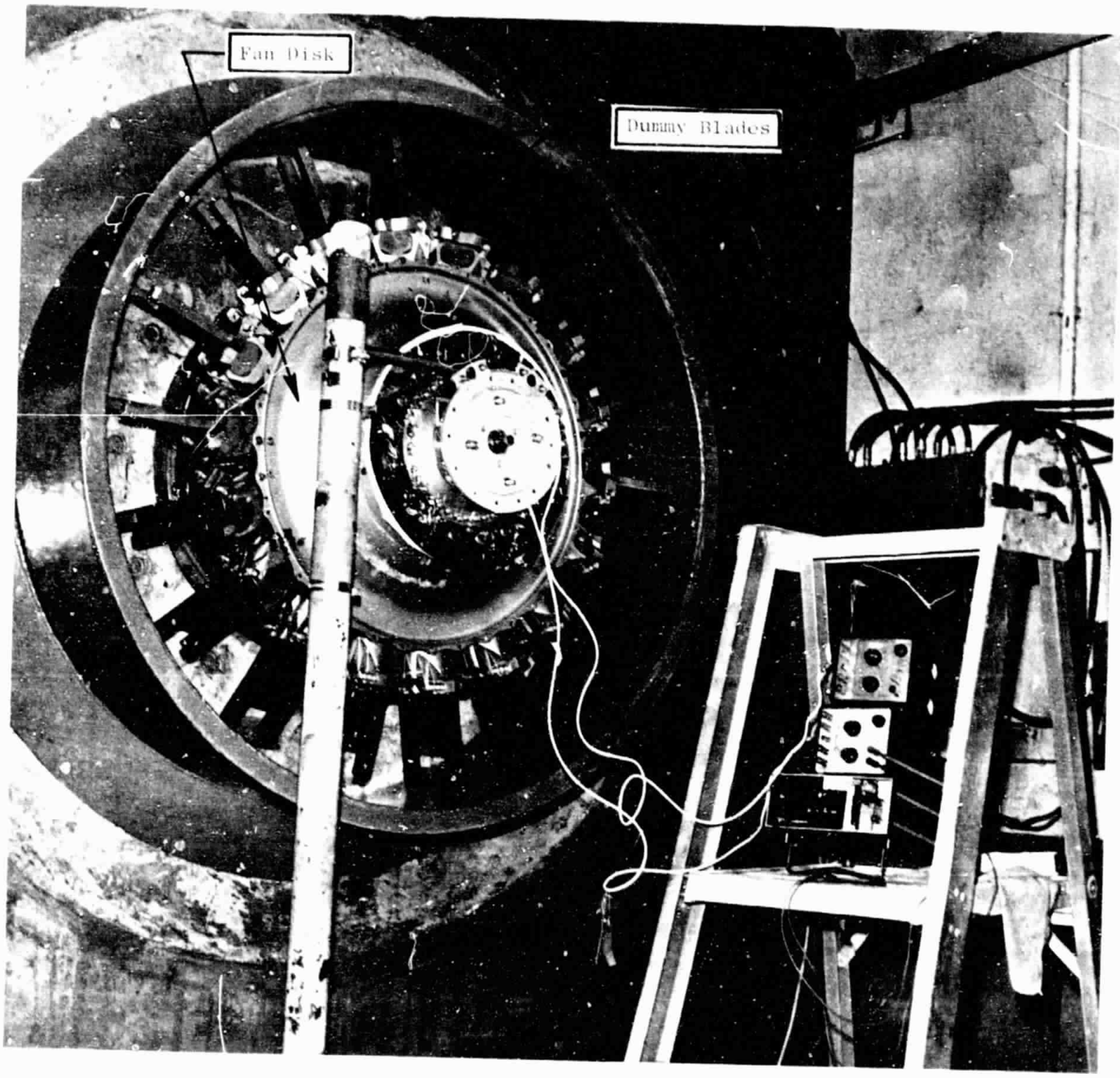

Figure 7. Mechanically Driven Actuator.

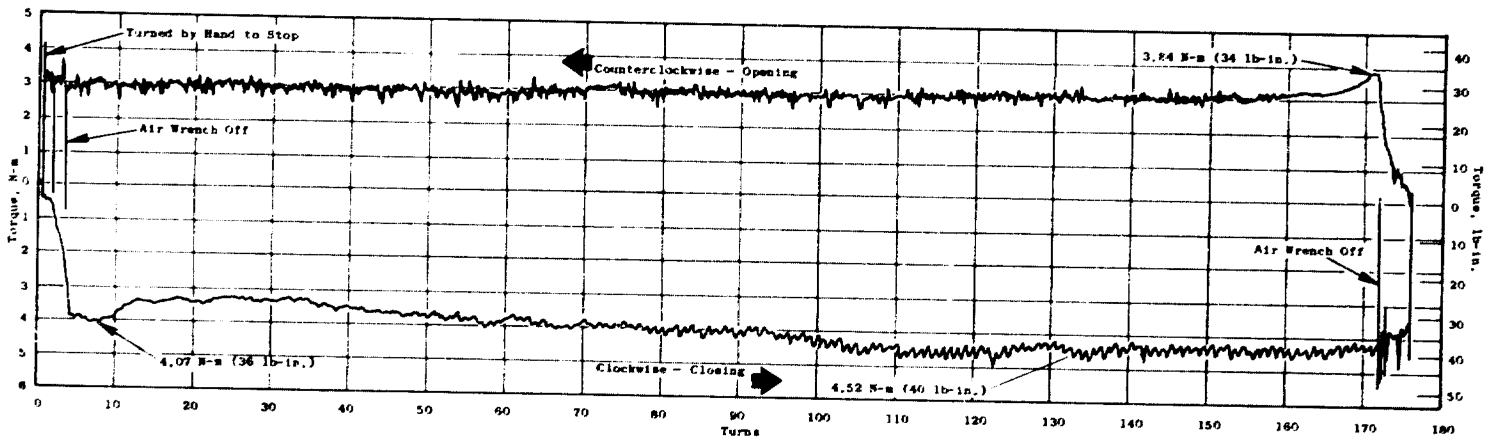

Figure 8. Torque of Actuator Through Full Stroke at Zero Fan Speed.

Table II. LVDT Reading Versus Fan Blade Angle Calibration - Static.

LVDT Reading No. 1	LVDT Reading No. 2	Blade Angle	Dovetail Angle	Direction of Motion
-0.0952		-27	- 52	Closing
+0.2389		- 3.5	- 28.5	Closing
+0.5044		+15.5	- 9.5	Closing
+0.6834	+0.66	+28.3	3.3	Closing
+0.6466	+0.6266	+28.3	3.3	Opening
+0.5786	+0.5595	+23.75	- 1.25	Opening
+0.2893	+0.2773	+ 3.16	- 21.84	Opening
+0.0088	+0.0051	-16.67	- 41.67	Opening
-0.3102	-0.3060	-39.41	- 64.41	Opening
-0.6906	-0.6781	-66.33	- 91.33	Opening
-0.8949	-0.8766	-81.16	-106.16	Opening
-0.9710	-0.9505	-86.50	-111.50	Opening
-1.027	-1.002	-90.50	-115.50	Opening
-0.649	-0.638	-66.50	- 91.5	Closing
-0.362	-0.357	-46.17	- 71.17	Closing
-0.0921	-0.0935	-26.72	- 51.72	Closing
+0.2493	+0.2379	- 2.42	- 27.42	Closing
+0.5011	+0.4828	+15.42	- 9.58	Closing
+0.7087	+0.6860	+30.25	5.25	Closing
+0.8112	+0.7869	+37.47	12.47	Closing

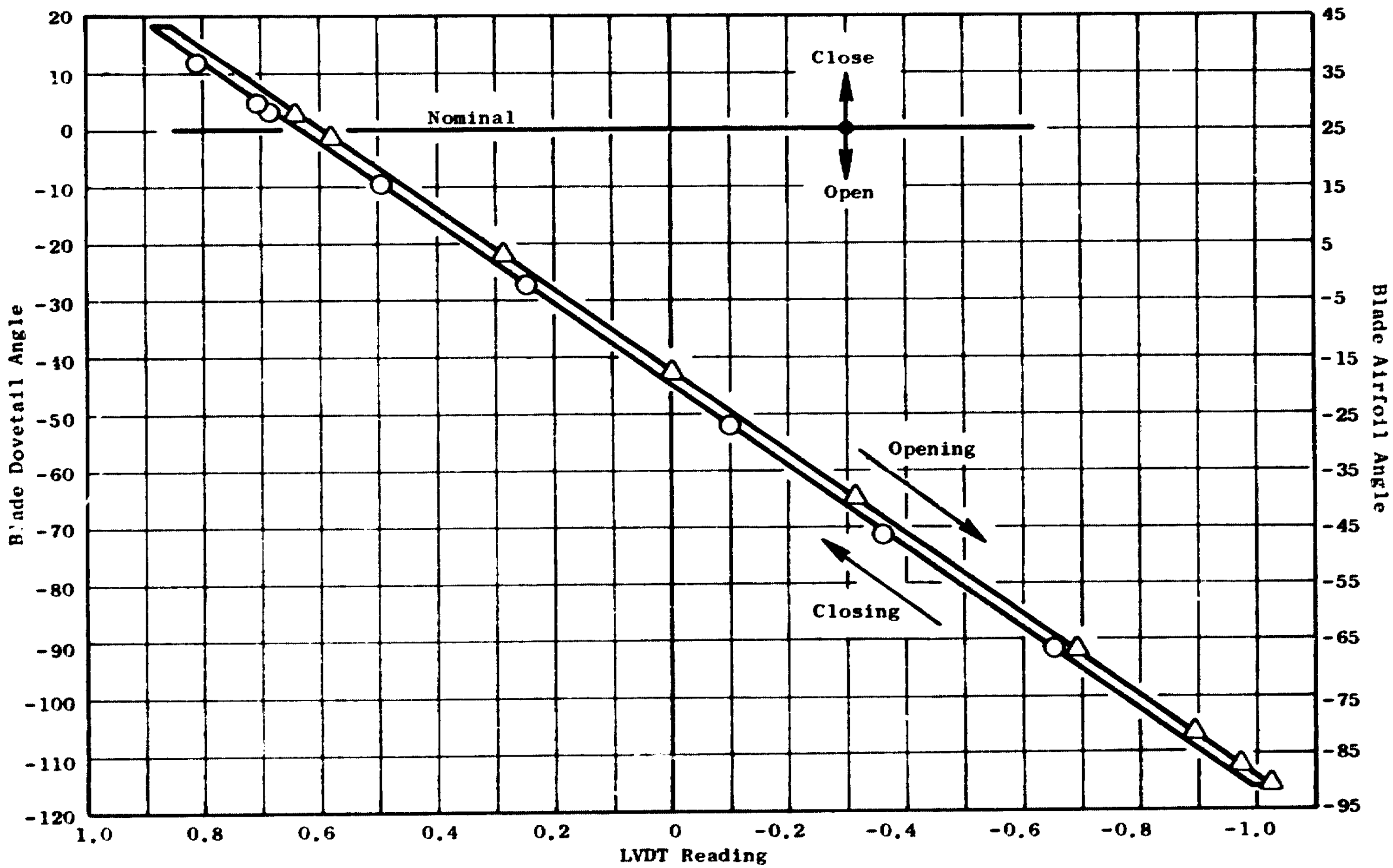

Figure 9. LVDT Reading Versus Fan Blade Angle Calibration (LVDT No. 1 Only).

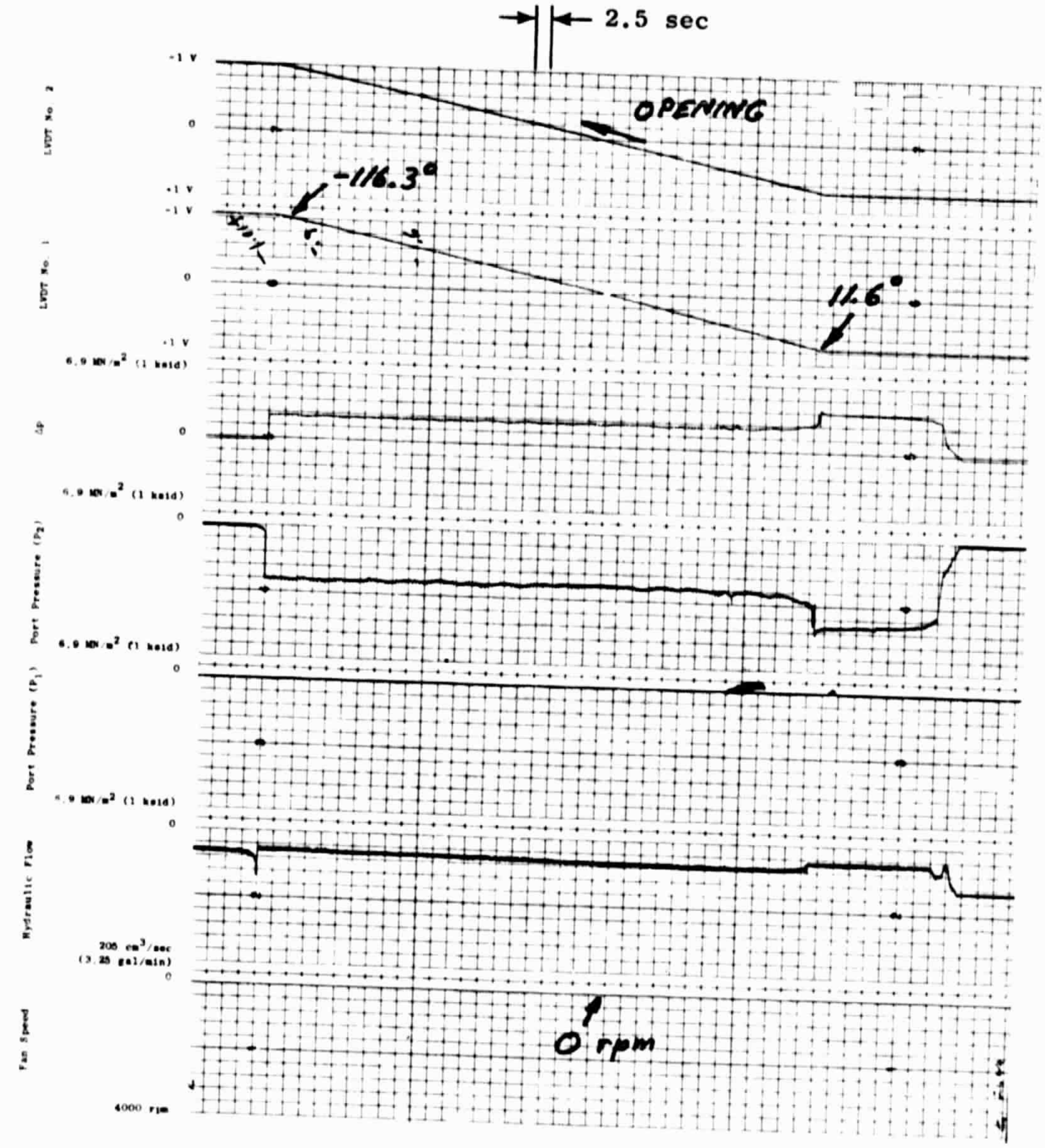

Figure 10. Zero Speed Checkout of Actuator (Opening Direction).

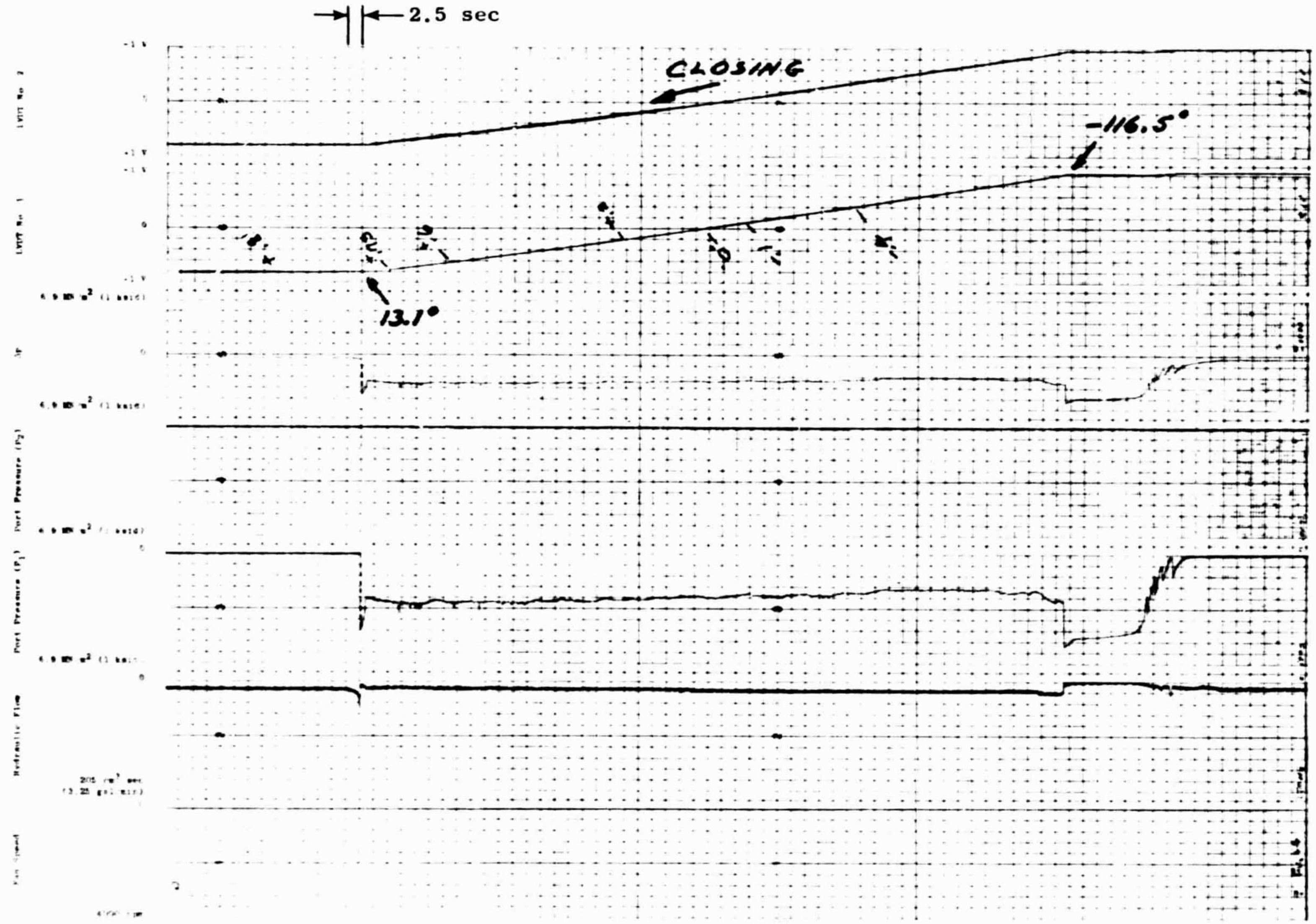

Figure 11. Zero Speed Checkout of Actuator (Closing Direction).

Table III. Mechanical Drive Versus Hydraulic-Motor Drive Data.

Direction	Mechanically Driven Torque		Hydraulic Motor Torque	
	To Start	To Sustain	To Start	To Sustain
Opening	3.84 N-m (34 lb-in.)	2.94 N-m (26 lb-in.)	3.16 N-m (28 lb-in.)	3.39 N-m (<30 lb-in.)
Closing	4.07 N-m (36 lb-in.)	4.52 N-m (40 lb-in.)	4.29 N-m (38 lb-in.)	3.39 N-m (<30 lb-in.)

Table IV. Motor Stall Torque and Leakage Data.

Direction	ΔP		Torque		Leakage	
	MN/m^2	(psi)	N-m	(lb-in.)	cm^3/DRC	(gpm)
Closing	3.447	(500)	3.00	(26.6)	-	-
	6.895	(1000)	4.80	(42.5)	12.5	(0.198)
	10.342	(1500)	-	-	16.7	(0.264)
	13.790	(2000)	11.83	(104.7)	16.7	(0.264)
	17.237	(2500)	15.05	(133.2)	17.8	(0.282)
	20.684	(3000)	18.87	(167.1)	17.8	(0.282)
	23.442	(3400)	21.08	(186.6)	18.5	(0.293)
	1.896	(275)	-	-	5.4	(0.085)
	5.171	(750)	-	-	9.2	(0.146)
Opening	1.724	(250)	0.08	(0.7)	-	-
	3.447	(500)	2.01	(17.8)	4.3	(0.068)
	5.171	(750)	3.14	(27.8)	7.1	(0.112)
	6.895	(1000)	5.08	(45)	11.9	(0.189)
	10.342	(1500)	8.25	(23)	12.2	(0.193)
	13.445	(1950)	11.21	(99.2)	12.5	(0.198)
	17.237	(2500)	14.76	(130.6)	12.2	(0.193)
	20.684	(3000)	18.18	(160.9)	10.4	(0.165)
	23.442	(3400)	20.37	(180.3)	10.9	(0.173)

This low speed checkout was accomplished with the slave control system as shown in Appendix A, Figure 4.0. MIL-L-23699 (Shell No. 555) was used as a hydraulic fluid. Figures 12 and 13 show the actuator characteristics at 1000 rpm fan speed.

Blades were actuated in both directions from approximately +7° to -114° at very low actuation rates (approximately 1.3°/sec). The hydraulic motor ΔP to start motion in the open and closed direction was 1.93 MN/m^2 (280 psid) and 1.65 MN/m^2 (240 psid) respectively. The motor torque required (approximately 1.13 N-m (10 lb-in.) at 1000 rpm was less than the torque required at 0 rpm because the preloaded trunnion-sliding bearings are unloading as the rolling-element bearings pick up the load.

4.3 OPERATIONAL CHARACTERISTICS AT SLOW ACTUATION RATES

Still using the slave control system, the blade angle at which maximum hydraulic motor ΔP occurred was determined. This was accomplished at 1000 rpm fan speed driving the fan blades in a closing direction. The maximum-load point occurs at approximately -65° in the closing direction as can be seen in Figure 13. Refer to Figure 1.0 of Appendix A for predicted value of about -75° for maximum load.

At this time the "breadboard" digital control was installed and used for the remainder of the test.

Starting at 2500 rpm fan speed and increasing in increments of 200 rpm up to 3350 rpm, the blades were actuated ±30° from the maximum-load point (-65°). No problems were encountered at any of these fan speeds. Figures 14 and 15 show typical characteristics at the maximum speed of 3350 rpm.

During this test, blade angle movements from the maximum-load point were made in the closing direction (motor driving), and the hydraulic-motor ΔP required to start motion is shown in Table V.

Table V. Hydraulic Motor ΔP to Start Motion.

Fan Speed	Blade Angle Change	ΔP
2900 rpm	-65.2° to -33.9°	11.032 MN/m^2 (1600 psid)
3100 rpm	-65.2° to -33.9°	16.547 MN/m^2 (2400 psid)
3350 rpm	-65.2° to -33.9°	18.754 MN/m^2 (2720 psid)

The hydraulic motor ΔP required to move the blades from the nominal position ±5° was also determined in a fan speed range of 2500 to 3350 rpm

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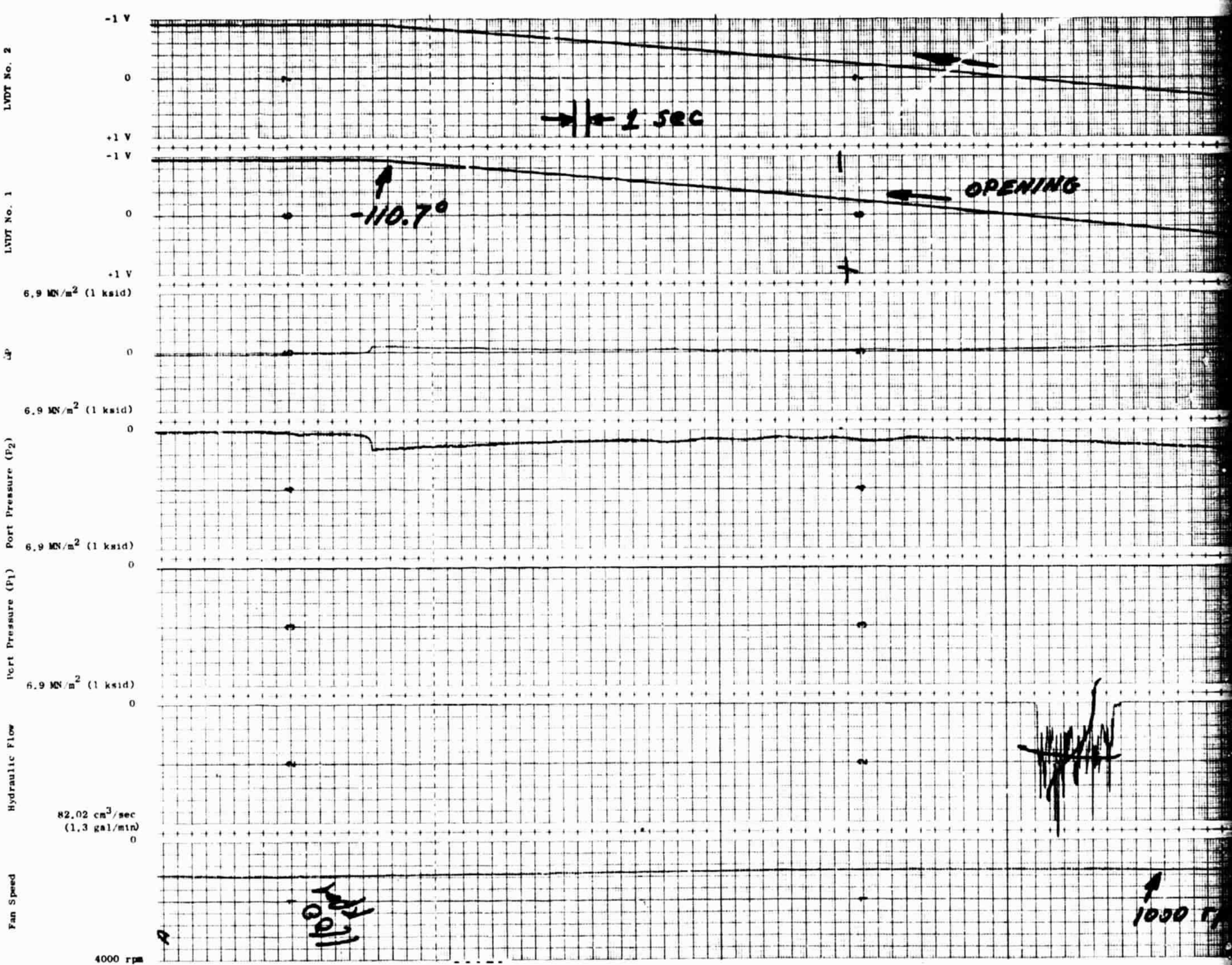
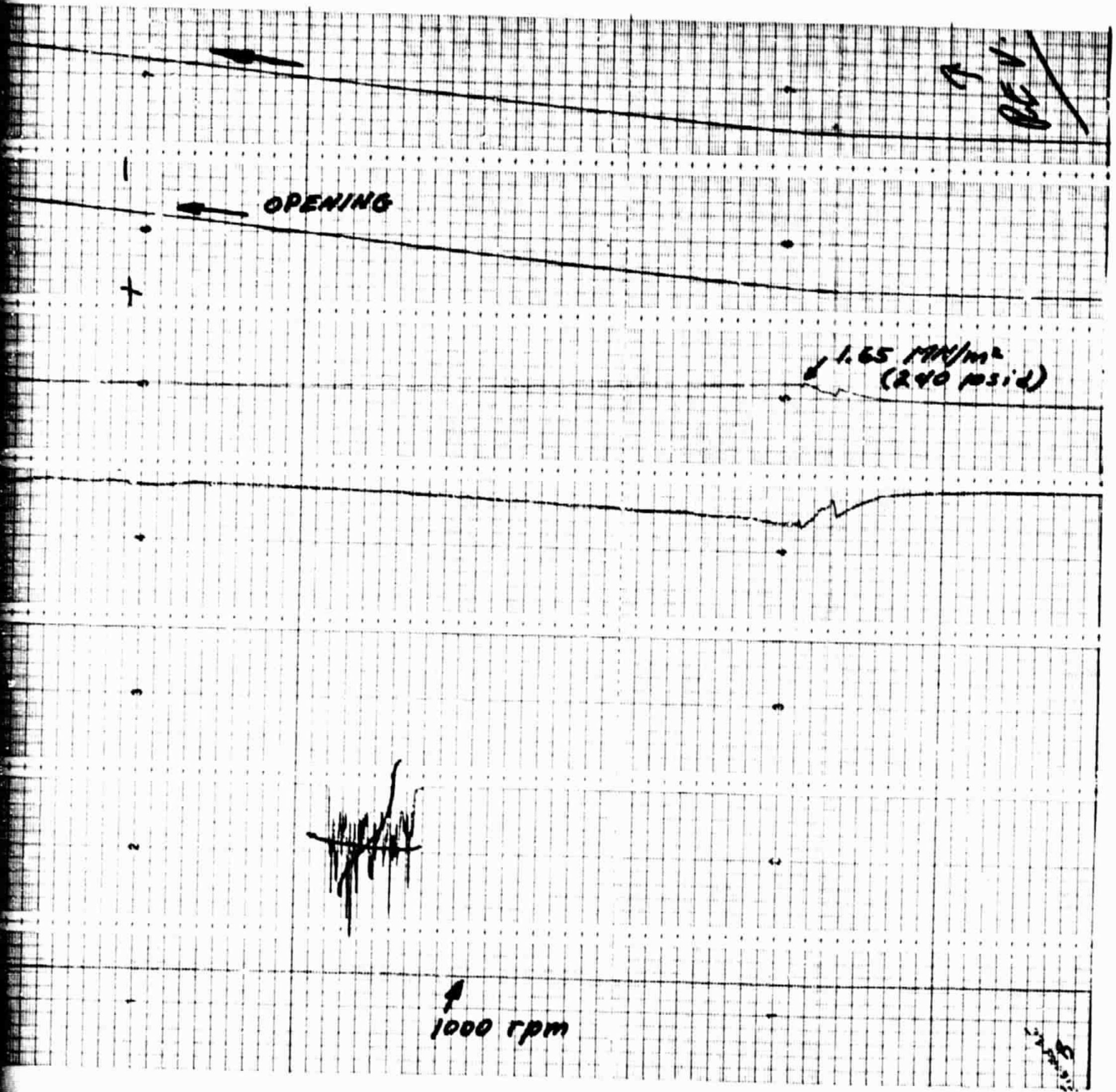


Figure 12. Actuator Characteristics (Opening Directio:n) at 10



teristics (Opening Direction) at 1000 rpm.

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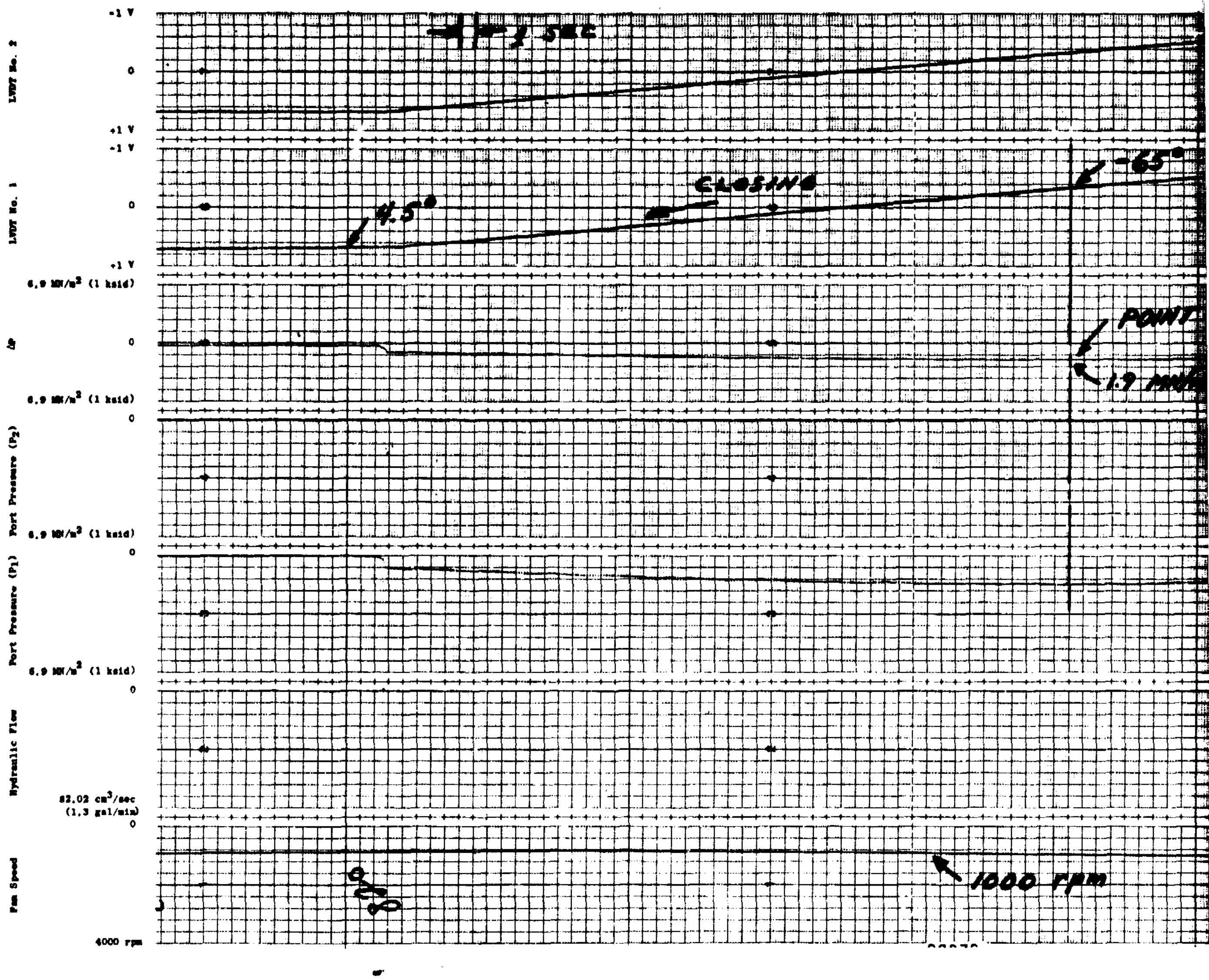
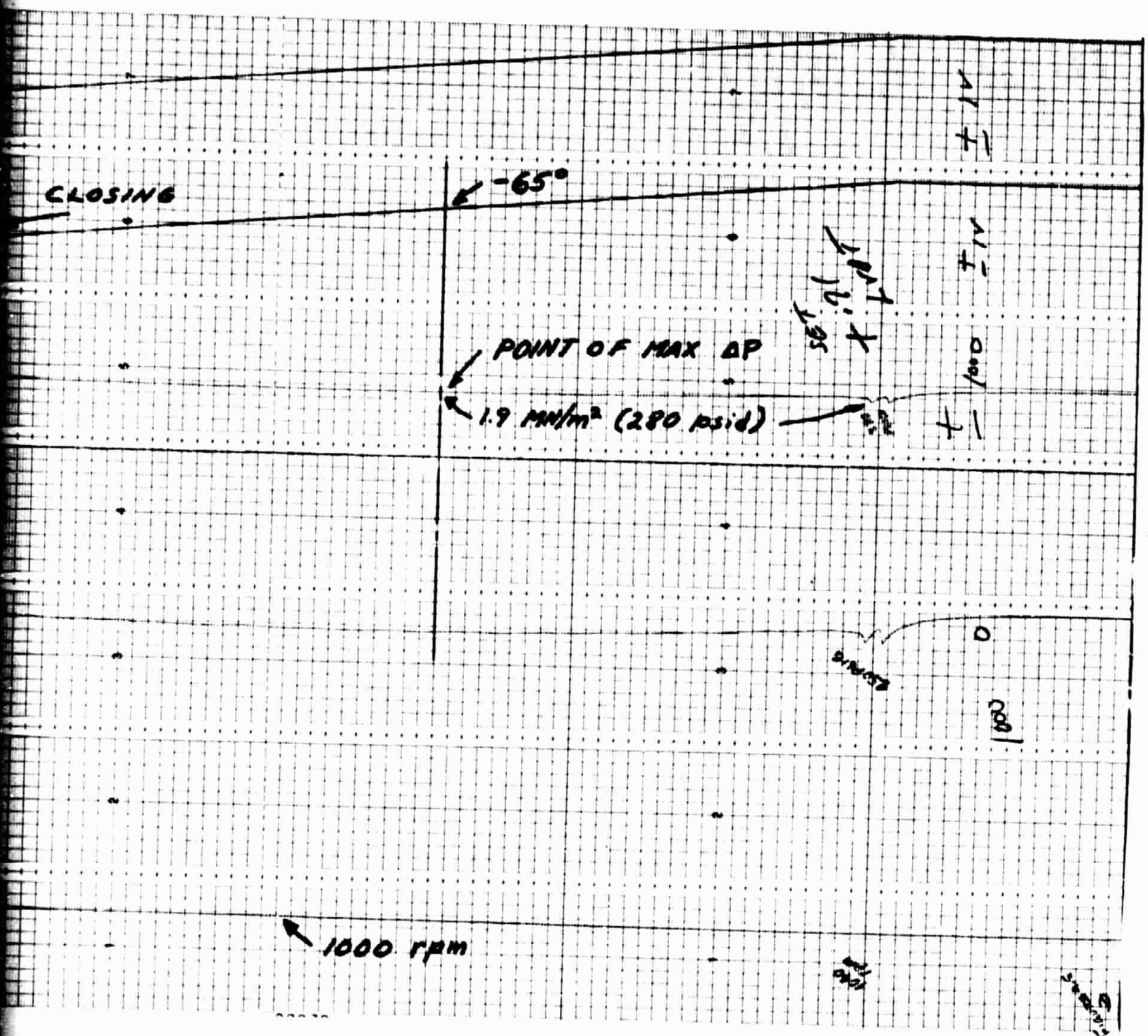


Figure 13. Actuator Characteristics (Closing Direction) at



Characteristics (Closing Direction) at 1000 rpm.

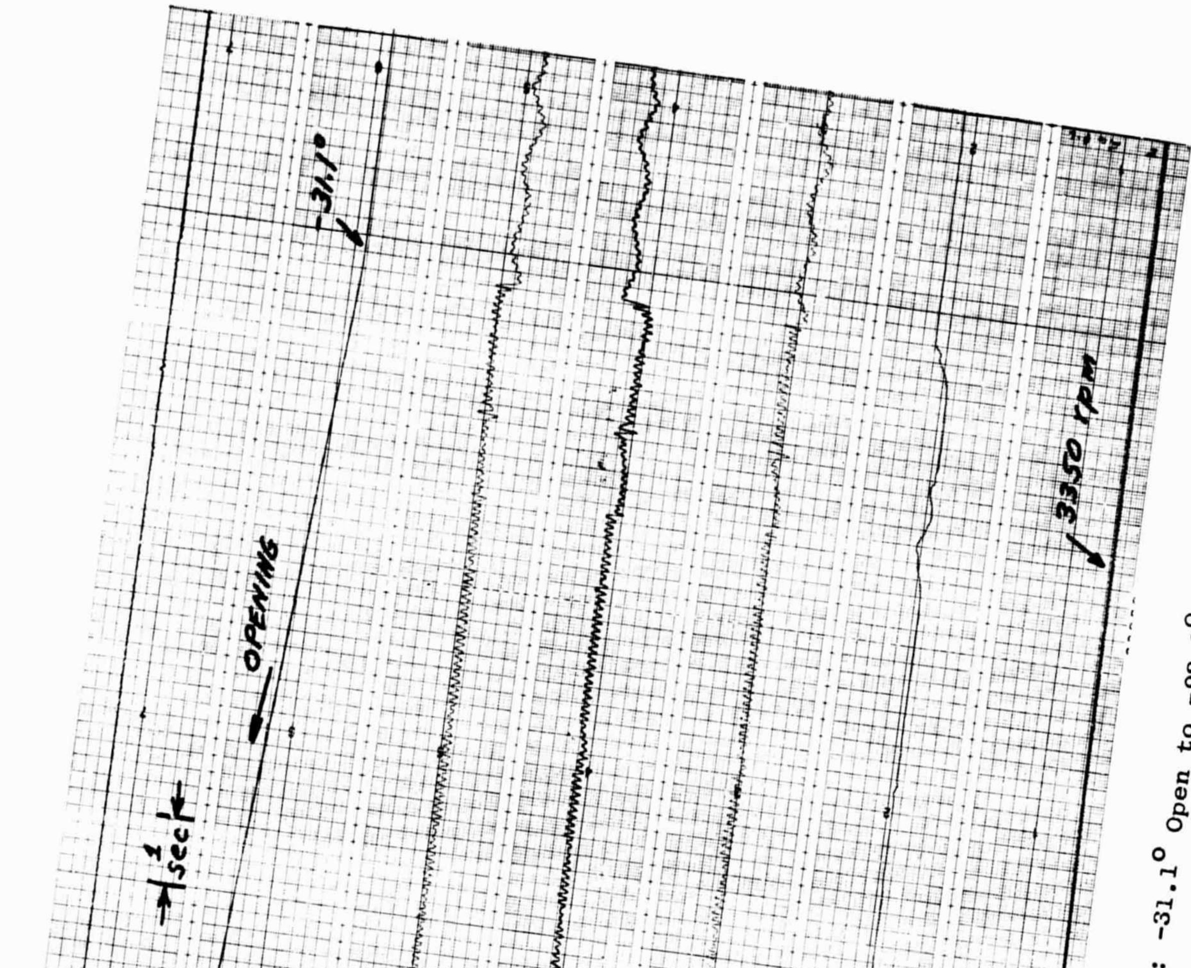


Figure 14. Blades Opening: -31.1° Open to -92.2° Open at 3350 rpm.

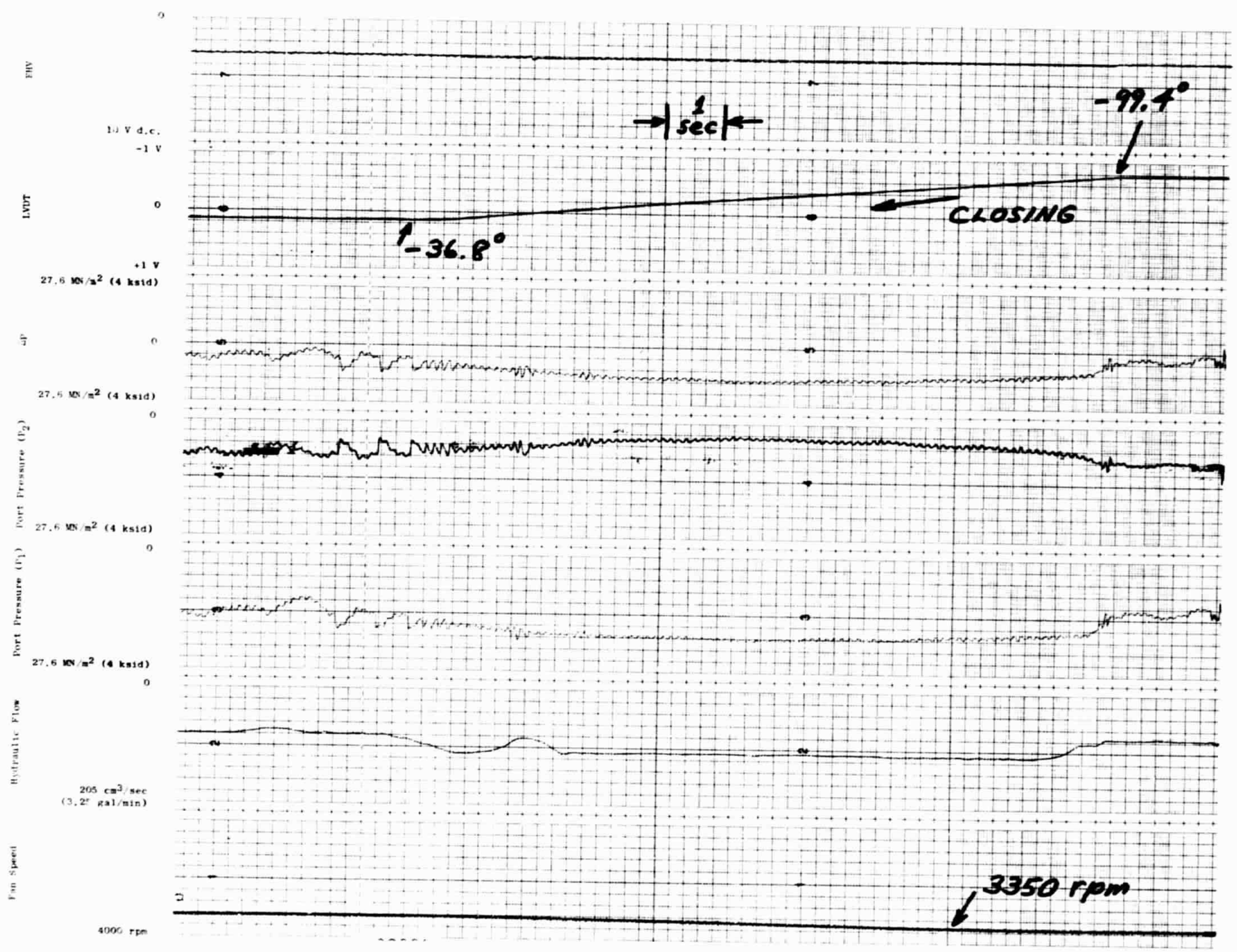


Figure 15. Blades Closing: -99.4° Open to -36.8° Open at 3350 rpm.

in increments of 200 rpm. A driving load is required to open the blades at these blade angles and the required hydraulic motor ΔP at a fan speed of 3350 rpm is shown in Figure 16. The maximum ΔP required during this traverse was 12.135 MN/m^2 (1760 psid). Table VI gives the maximum ΔP for all the speed points tested.

Table VI. Maximum Hydraulic ΔP During Traverse from +9° to 0° Blade Angles.

Fan Speed	ΔP
2500 rpm	6.619 MN/m^2 (960 psid)
2700 rpm	7.722 MN/m^2 (1120 psid)
2900 rpm	8.825 MN/m^2 (1280 psid)
3100 rpm	9.929 MN/m^2 (1440 psid)
3350 rpm	12.135 MN/m^2 (1760 psid)

Blades were also traversed between approximately +5 to -110° for fan speeds of 2500 to 3350 rpm in both the closing and opening direction in increments of 200 rpm. Figures 17 and 18 show the actuator characteristics at 3350 rpm. Table VII shows the ΔP occurring during the transient at a fan speed of 3350 rpm. During the test program rapid pressure fluctuations were recorded on the Sanborn strip charts as can be seen in Figure 19. The specific cause of these fluctuations is not known at this time but the following is noted. Since the magnitude and frequency of the pressure fluctuations decrease during the transients it is suspected that the prime cause of the pressure oscillations is associated with the pressure regulator in the slave hydraulic pump. On a steady state basis the magnitude is about 2.21 MN/m^2 (320 psid) which based on the UTW Build 2 testing is not sufficient to cause blade movement during engine operation. It does not appear that these fluctuations have any effect on the overall test results.

Table VII. Hydraulic Motor ΔP Required to Open and Close Blades at 3350 rpm.

Direction	Hydraulic Motor ΔP	
	Start Motion	Maximum ΔP
Open 5.9 to -107.8°	11.032 MN/m^2 (1600 psid)	12.135 MN/m^2 (1760 psid)
Close -110.8° to 3.0°	6.619 MN/m^2 (960 psid)	14.341 MN/m^2 (2080 psid)

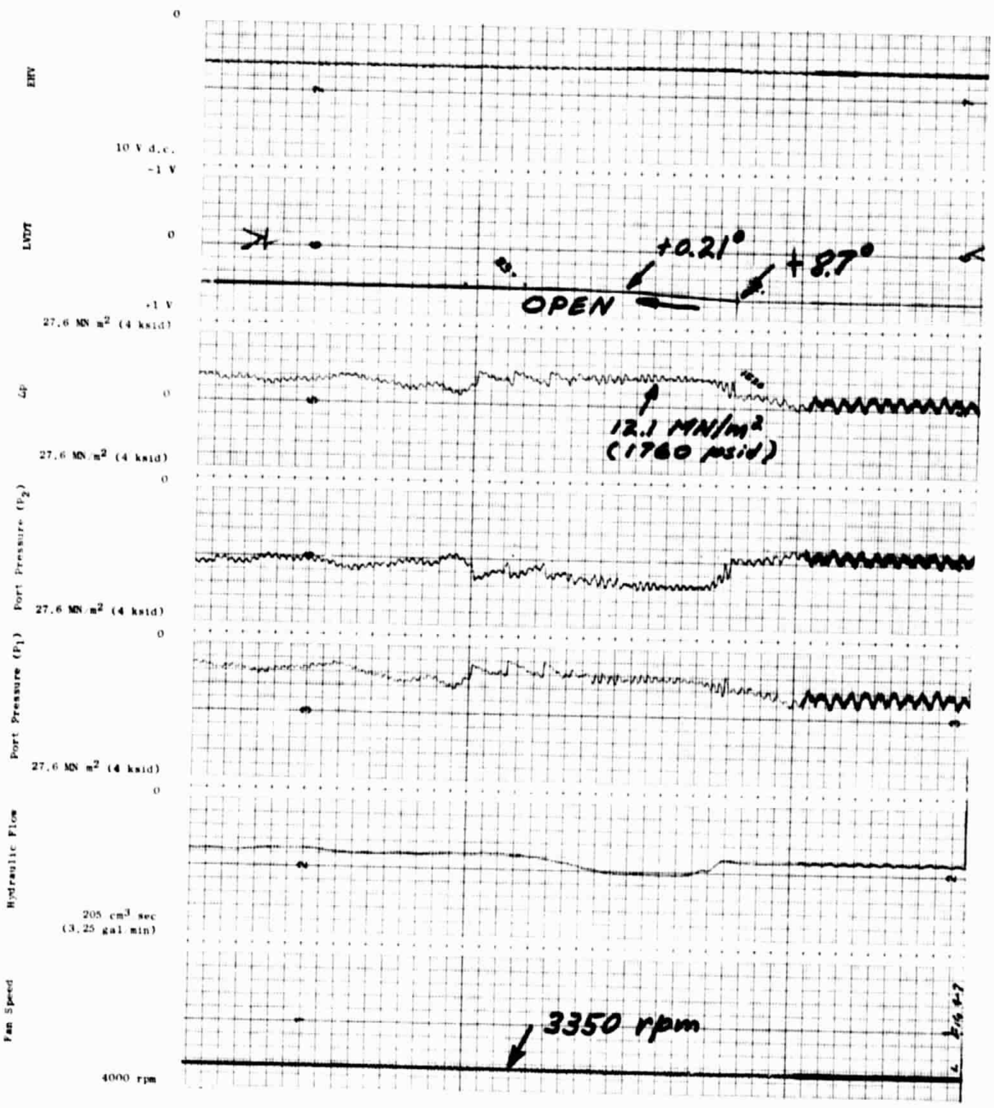


Figure 16. Blades Opening: + 8.7 to 0.21° at 3350 rpm.

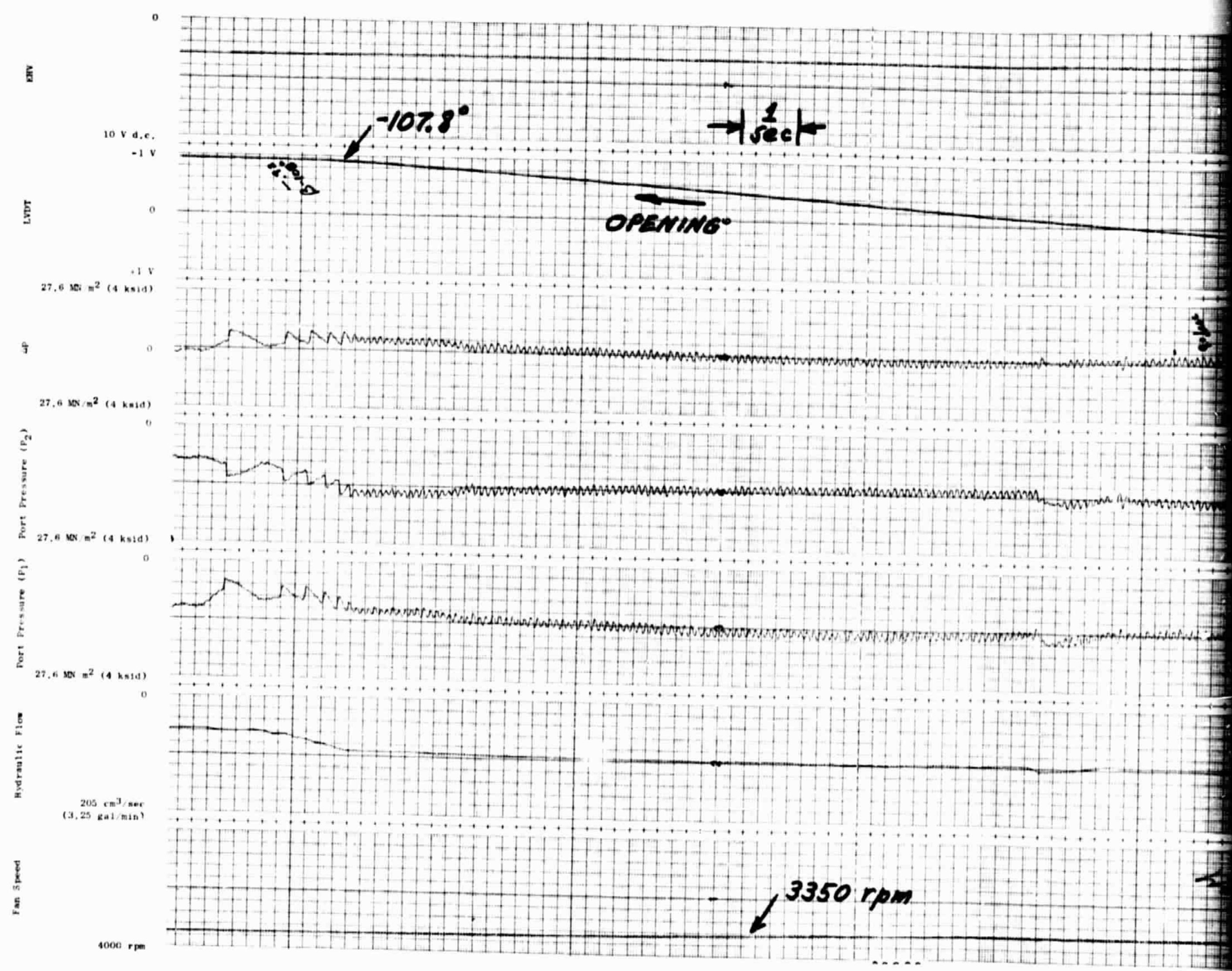
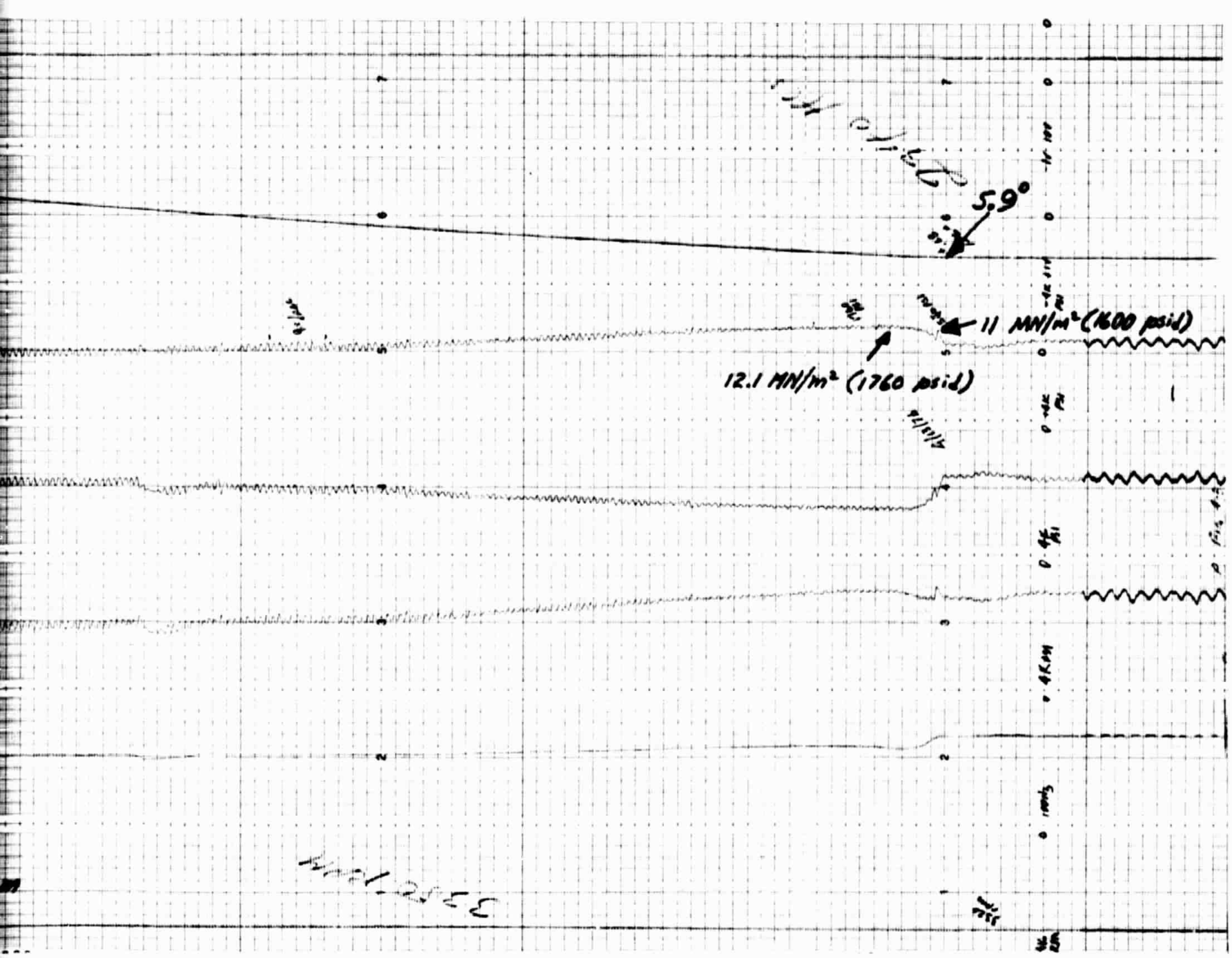


Figure 17. Blades Opening: 5.9° Closed to -107



ning: 5.9° Closed to -107.8° Open at 3350 rpm.

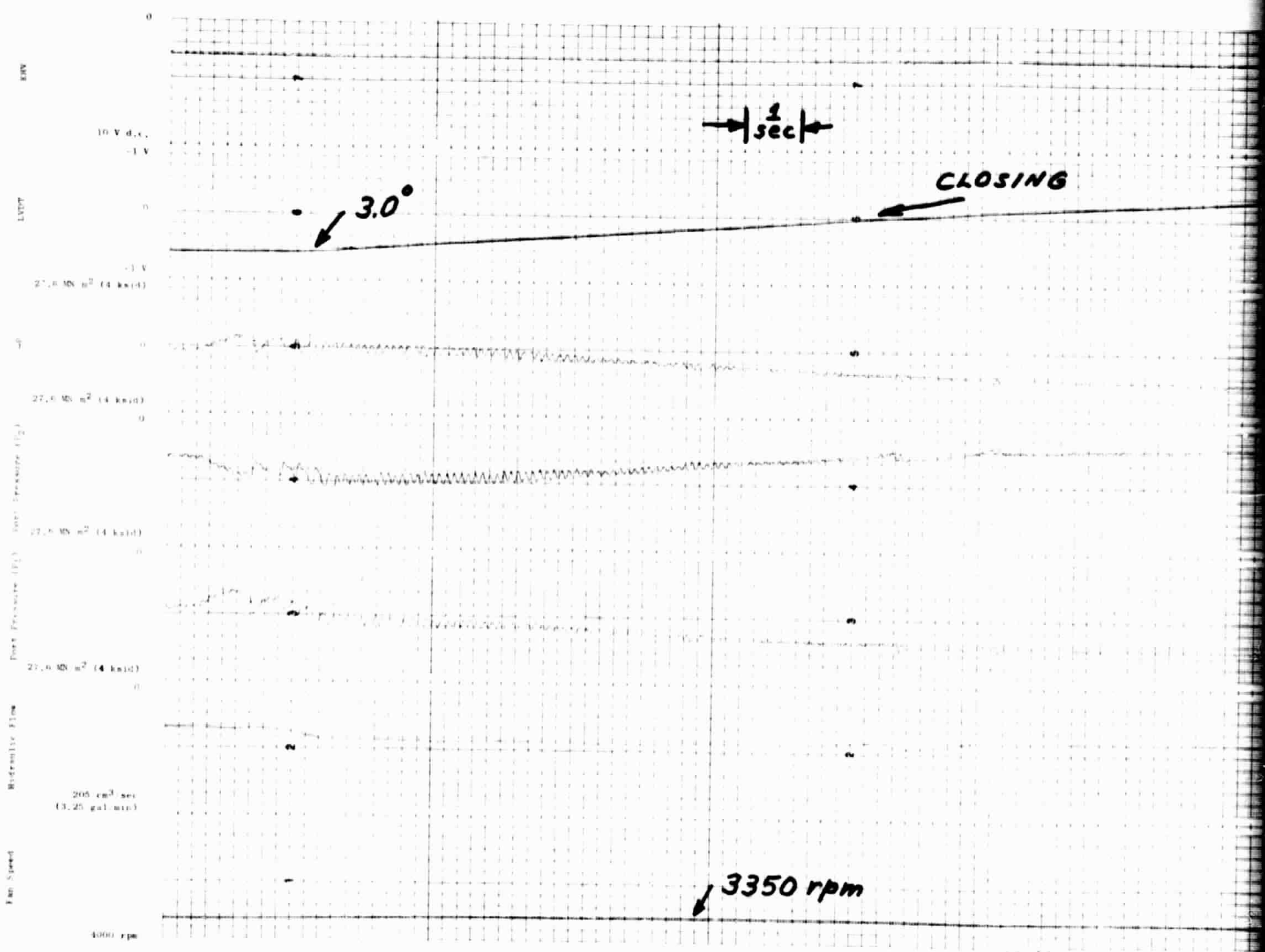


Figure 18. Blades Closing: -110.8° Open to 3.0° Clo

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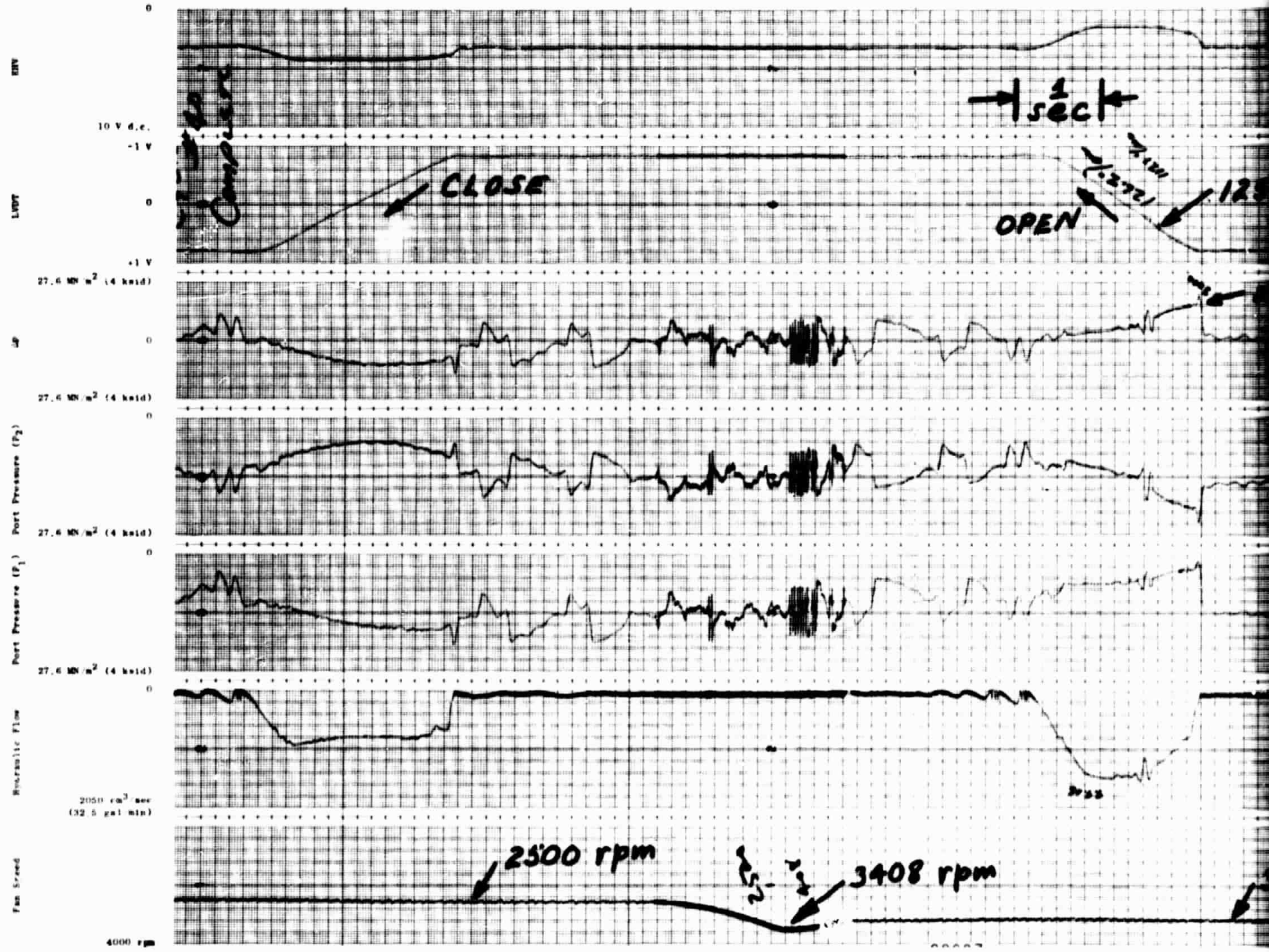

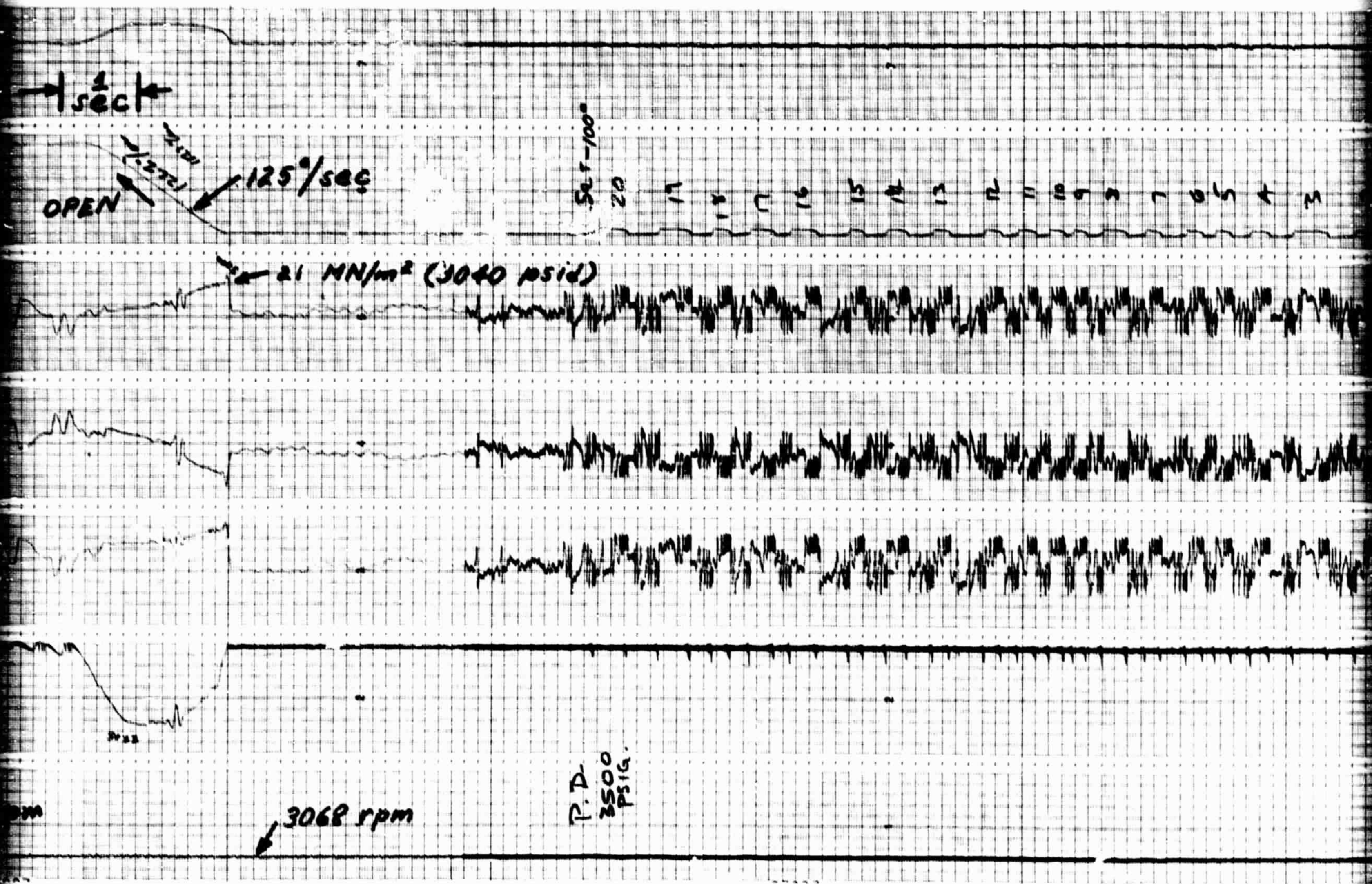

Figure 19. Endurance Cycle No. 40.

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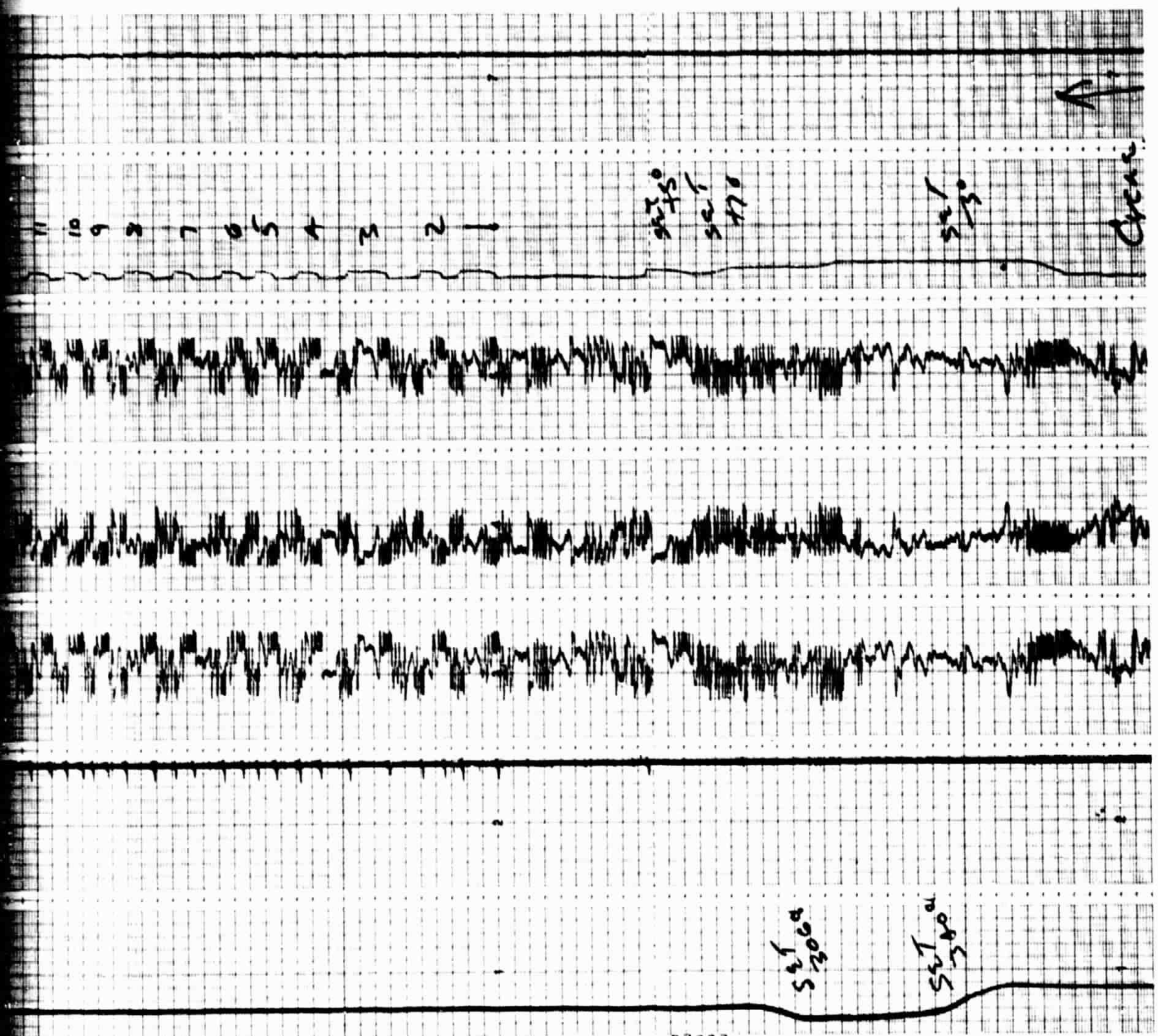

Two short cyclic tests were then performed. The actuator was cycled 10 times ±5° from the nominal blade angle at a fan speed of 3350 rpm. The actuator was also cycled 15 times approximately ±20° from the blade-angle setting that required the maximum ΔP (-65°). No problems were encountered during these cycling tests.

This completed all the slow actuation-rate testing. The orifice to restrict the hydraulic-motor flow was removed and in all subsequent testing the full flow capacity of the motor was available.

4.3.1 No-Back Test Results

With the blades set at an angle of -65° (point where maximum torque is needed to hold blade) the "no-back" would not hold the blade position above 2500 rpm fan speed. Consulting with the manufacturer of the "no-back" revealed that there was insufficient shim thickness locating the ball cam plate. This allowed the three loading balls to overtravel circumferentially and not provide sufficient axial force on the friction disks.

It was decided to complete the remainder of the test using the hydraulic motor to hold the blade position and then reshim the "no-back" and run a separate "no-back" test.

With all other testing completed, the "no-back" was reshimmed using a procedure obtained from the manufacturer. Measurements showed that a 0.673-M-n (0.0265-in.) shim was required to properly load the friction disk and only 0.1651 mm (0.0065 in.) was originally installed. Additional shims were added and the unit was returned to test.

During the separate "no-back" test, the hydraulic motor was not mated with the actuator; thus, only the "no-back" could hold blade position. The blade angle was set at the approximate maximum-load point of -65° and the angle was measured with the clinometer. The measured angle after running at 3415 rpm for 3 minutes was within 0°10' of original setting. This test was performed twice, and both times the blades remained in position.

4.4 BLADE ANGLE ACCURACY AND "JOGGING" CAPABILITY

As stated previously the measured static hysteresis was 3° of blade angle. To study the effect of this hysteresis during operation a blade angle setting accuracy test was performed. With the fan rotating at 3408 rpm the fan blade angle was set at nominal position from an open blade angle setting. At shutdown the blade angle was measured and recorded. The fan was then run at speeds of 1000 - 3408 rpm and various small blade angle changes were made in both open and closing directions. The final blade angle adjustment was back to the nominal position but from a more closed blade angle setting. At shutdown the blade angle was again measured and recorded. The difference between the measured nominal fan blade angles was 0°07', when approached from either an open or closed fan blade angle. The measured results are shown in Table VIII.

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Table VIII. Blade Angle Setting Accuracy Test.

Direction of Approach To Nominal	LVDT	Measured Blade Angle At Shutdown
From Opened	+0.5994	23°54'
From Closed	+0.5991	23°47'
		Δ = 0°07'

During the blade accuracy setting test a light was focused on the face of the dummy blades. Any small changes in blade angle could be visually seen as a shadow movement. At 1000 to 3408 rpm, blade angles were changed by small increments (0.2° to 1.5°) during which time the changes in light pattern were recorded by NASA and GE observers; Table IX describes this information.

Table IX. Visual Observation from "Jogging" Test.

rpm	Δ Blade Angle Set by Digital Control	Remarks
1000-3408	1.5°	Movement observed especially noticeable at 2400 rpm
2400	1.0°	Movement observed
2400	0.5°	Movement observed
2400	0.2°	Movement observed

4.5 CYCLIC ENDURANCE TEST

A fifty-cycle endurance test was completed using the test cycle shown in Table I. Figure 19 shows data representative of one of these cycles. The average maximum hydraulic motor ΔP required when going into reverse was 17.982 MN/m^2 (2608 psid) at 3068 rpm. The maximum actuation rate was 125°/sec and the average rate of all reverse cycles was 119.6°/sec. No problems occurred during this cyclic test.

4.6 INSPECTION OF HARDWARE AFTER TEST

Certain areas of the actuator were selected for posttest visual inspection. These included the following:

- Ball screw and spline ball tracks
- Forward axial stop
- Involute splined output member of the ball spline
- Differential gears
- Blade pinion and ring-gear tooth meshes

None of the hardware showed any signs of distress. The forward stop had been engaged several times during the test, and indications of this engaging action could be seen on the stop jaws. The disk plates in the axial-stop assembly were in good condition. All hardware was in excellent condition. Figures 20 through 23 shows photographs of the major hardware after the completion of the whirligig test.

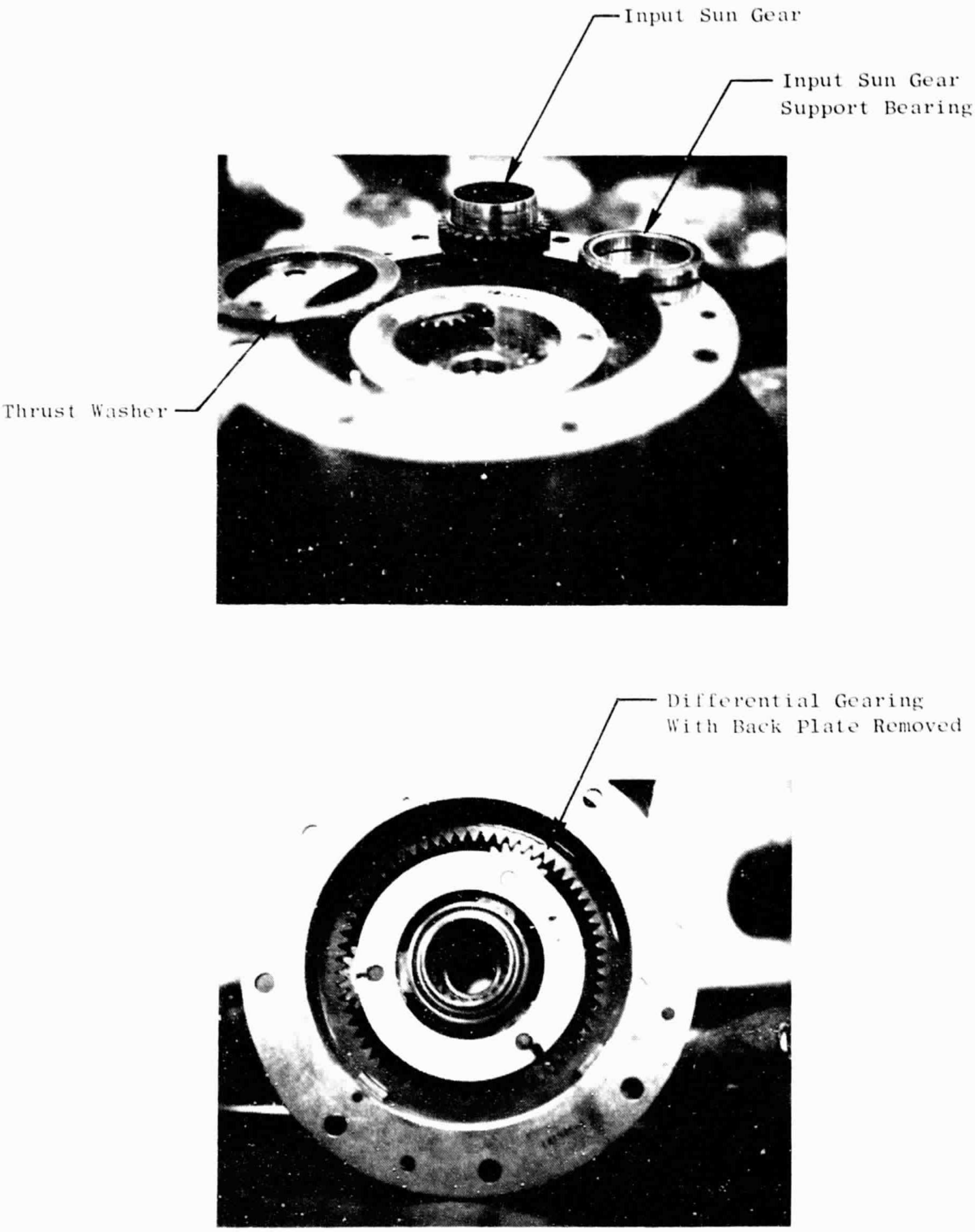

Figure 20. Differential Gearing Assembly.

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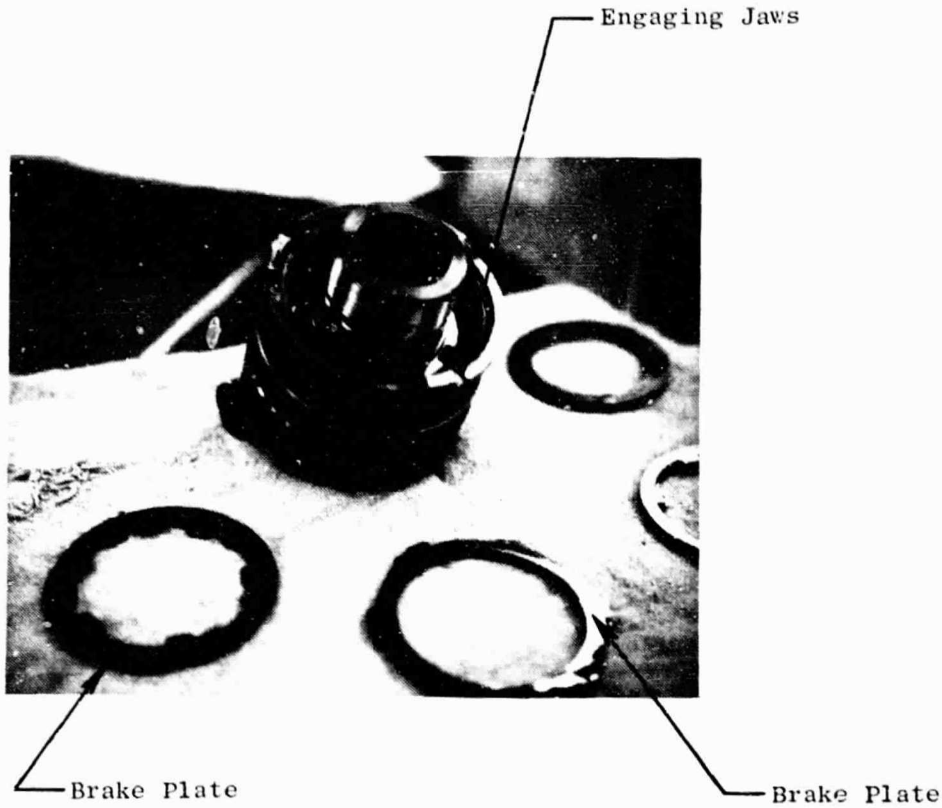


Figure 21. Forward Stop Assembly.

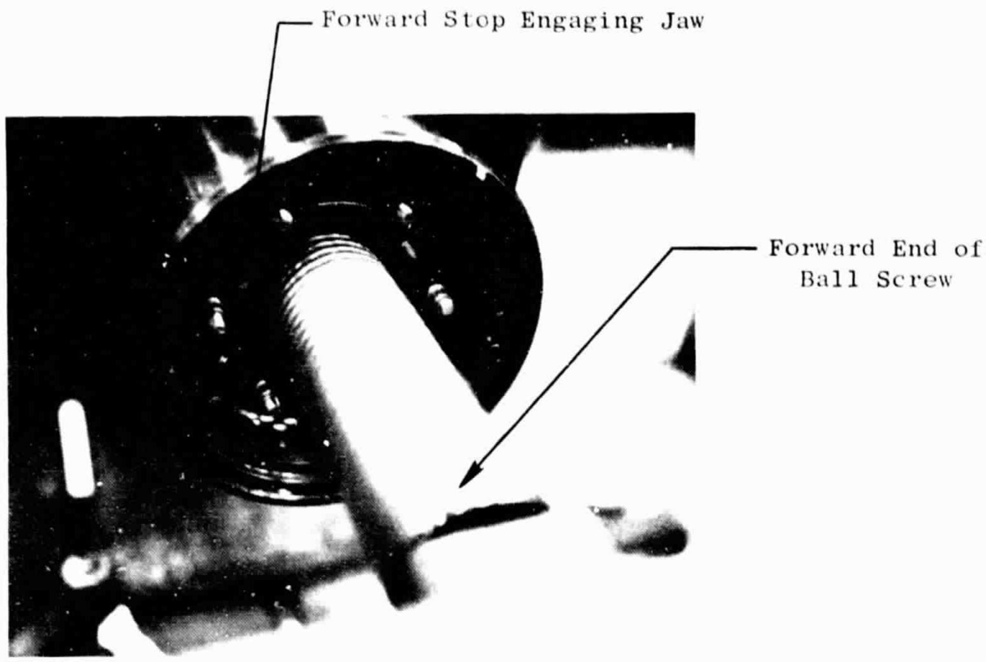
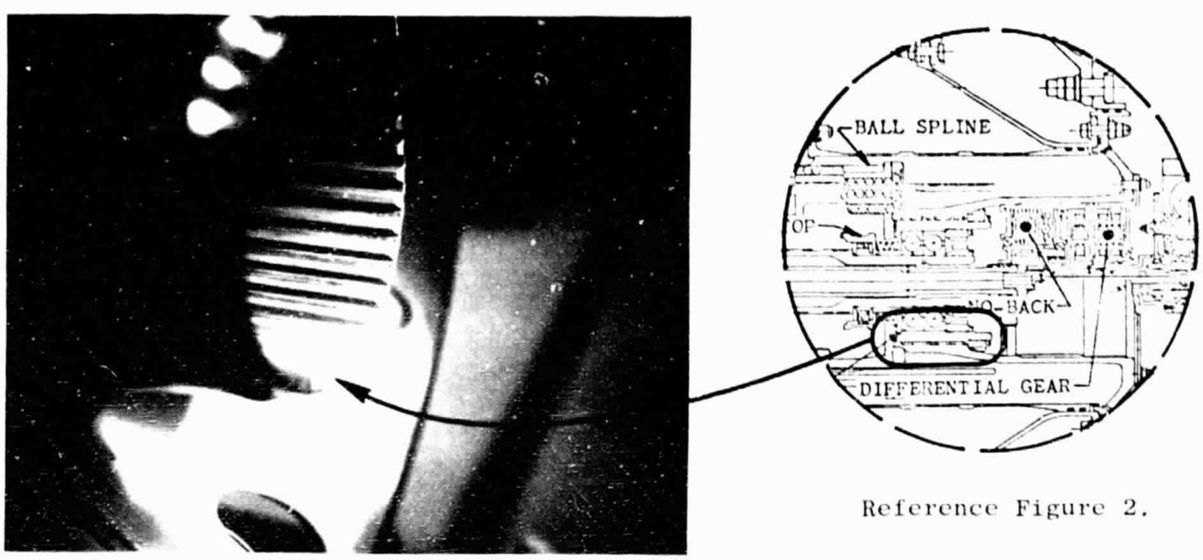


Figure 22. Ball Screw Assembly.



Reference Figure 2.

Figure 23. Actuator Drive Spline.

5.0 REFERENCES

1. The General Electric Company "UTW Engine Final Design Report," NASA CR-134847.

2. The General Electric Company "Ball Spline Pitch Change Mechanism Design Report," NASA CR-134873.

APPENDIX A - GENERAL ELECTRIC TEST PROJECT SHEET

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DATE 3/29/76 **TEST PROJECT SHEET *** NO.

TITLE Operational Testing of GE Variable Pitch Actuator

ENGINE MODEL NO. QCSEE — AUTHORIZING PLAN NO.

TO W.C. Moore/E188/3624 — REQUESTED COMPL. DATE

FROM R.H. Griswold/C.L. Broman — PHONE 4442/2964 — APPROVED

OUTLINE: PAR. I PROBLEM TO BE SOLVED; II PARTS TO BE TESTED; III TEST DESIRED; IV TEST SET UP & INSTRUMENTATION; V SPECIAL INSTRUCTIONS; VI REFERENCES

I) Problem to be solved

A whirligig test is to be provided for the GE variable pitch actuator to ensure design and structural adequacy before engine testing. Testing will include actuation at 100% fan speed and actuation rates representative of engine requirements.

II) Parts to be tested

Item	Title	Part Number	Qty
1	Disk Assembly	4013213-380	1

The following parts in this assembly are not required: PPN 830B1, 830A2, 830A3, 830B4, 830B2, 830A6, & 830A0.

Item	Title	Part Number	Qty
2	Blade, Simulated	4013151-884P02	18
3	Actuator Assembly	4013205-001 Sh 5	1

The following parts in this assembly are not required: PPN 8400H, & 8400J.

III) Test required

1) Initial manual checkout

a) This checkout is to be completed with the hydraulic motor and tube assembly not mounted.

* THIS DOCUMENT DOES NOT AUTHORIZE EXPENDITURES

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TPS ACKNOWLEDGEMENT

ACCEPTED ☐ REJECTED ☐

ASSIGNED TO ENG. #

SCHED. WK. TO TEST

RESPONSIBLE ENGINEER

COMMENTS

APPROVED DATE

b) Using special drive quill rotate actuator by hand through full stroke (approximately 170 turns total) observing any excessive drag. Record lowest and highest torque. Individual blade trunnion breakaway torque to be recorded at rotor buildup. Actuate in both directions and measure breakaway torque.

c) LVDT's are to be energized during this checkout and blade angle versus LVDT reading to be recorded for angles listed below. Record in both directions.

Angles to be checked are:
1) 10° Closed
2) 5° Closed
3) Nominal
4) 5° Open
5) 20° Open
6) 40° Open
7) 60° Open
8) 80° Open
9) 90° Open
10) 100° Open
11) 116.0° Open

2) Checkout with fan rotor at 0 rpm

a) Pressurize motor gradually to 3400 psi max if required and slowly actuate from 10.1° closed to 116.0° open. Motor flow to be less than 5 gpm (approximately 2500 motor rpm).

b) Motor flow, ΔP, time, and position readout to be recorded through total range of blade travel. Record data in both directions of travel.

3) Checkout with fan rotating at 1000 rpm.

a) With fan rotating at 1000 rpm check for oil leaks.

b) Set blade angle at approximately 80° open and note any blade movement with motor ports not pressurized. ("No Back" holding)

c) Pressurize motor gradually up to 3400 psi max and slowly actuate from 5° closed to 110° open. Motor flow to be less than 5 gpm. Care must be taken not to engage stops. ("No Back" overhauling load from 25° open to 110° open - Ref. Figure 1).

d) Fan speed, motor flow, ΔP, time, and position readout to be recorded through total range of blade travel. Record data in both directions of travel.

4) Determine maximum actuation torque capability

a) Set blade angle at point that requires maximum motor pressure with blade in open position at 1000 rpm. Increase fan speed to 2500 rpm and then in increments of 200 rpm up to 3347 rpm.

b) At each fan speed determine motor ΔP and flow required to actuate blades continuously at least ±20° from original blade angle setting of step 4a. Record fan speed, motor flow, ΔP, time, and position readout.

c) Design Engineering must be consulted if blade angle setting will approach stops. (Blade angles greater than 110°).

d) At 3347 rpm set blade angle at point where maximum hydraulic pressure is required to drive it. Shut down and measure blade angle. Start and increase fan speed to 3447 rpm maintaining previously set and measured blade angle, hydraulic motor to be de-energized. Shut down and measure blade angle. At any speed where motor is not energized there should be no blade angle drift ("No Back" holding).

5) Actuation torque required at nominal blade angle setting

a) Set blade angle at nominal position and fan speed at 2500 rpm. Increase speed in increments of 200 rpm up to 3347 rpm.

b) At each speed determine motor ΔP and flow required to actuate at least ±5° from nominal blade angle setting. Also determine min ΔP to start blade movement.

c) Record fan speed, motor flow, ΔP, time, and position readout during actuation.

d) With blade angle measured and set at nominal position, increase fan speed to 3347 rpm, actuate blades ±5° several times and reset to nominal blade position, shut down and measure blade angle. Check repeatability in both directions.

e) With motor not energized note any tendency for blades to change position (Ref. 4d).

6) Actuation torque required for blade excursions from nominal to 100° open

a) Set blade angle at nominal position and fan speed at 2500 rpm. Increase speed in increments of 200 rpm up to 3347 rpm.

b) At each speed slowly increase hydraulic motor pressure until blade movement is noticed. Allow blade to travel to 95° - 100° open.

c) Record fan speed, motor flow, ΔP, position readout, and time during excursion.

7) Cycle test at nominal blade setting (10 cycles)

a) Set blade angle at nominal position and fan speed at 3347 rpm.

b) Actuate blade angle from at least 5° open to 5° closed and record fan speed, motor flow, ΔP, time, and position readout during actuation. Actuate for 10 cycles.

8) Cycle test at maximum torque point (15 cycles)

a) Set fan speed at 2841 rpm and blade angle at the point where maximum hydraulic pressure is required to actuate.

b) Close blade angle setting 20°.

c) Slowly actuate opening blade angle setting 40°.

d) Pressurize motor and close blade angle setting 40°.

e) Record in both directions fan speed, motor flow, ΔP, time and position readout during excursions.

f) Repeat steps (c) through (e) 15 times.

9) When all testing covered by steps 1-8 has been completed the test set up is to be revised to include the "bread board" control, representative of the engine digital control. (See fig. 5.0).

a) The "bread board" control LVDT calibration is to be made using data from step 1c.

b) (Accuracy check) with blade angle set at nominal, record actual and LVDT reading. Change blade angle in +.25 increments in 5 setps and record the actual and LVDT readings. Return to original reading in same steps and again record the actual and LVDT reading.

c) (Checkout bread board control/actuator compatibility) with fan speed set at 1000 rpm and hydraulic flow restricted to 5 gpm actuate between approximately 10.1° closed and 116° open in each direction.

d) (Rapid actuation testing) <u>with flow restrictor removed</u> actuate between approximately 10.1° closed and 116° open in each direction 5 times at fan speeds of 2500 rpm and 3068 rpm. Determine peak actuation rate and resultant average actuation rate.

e) (Jogging capability) at fan speeds of 0, 1000, 2500 and 3347 rpm determine the minimum change in blade angle ($.25^\circ$ Ref) obtainable with blade setting at nominal. Record LVDT reading, shut down and measure actual angles.

f) ("No back" holding test) with blade angle set at 2^{o} closed (take off) vary fan speed between 1000 and 3347 rpm. Hydraulic motor to be de-energized. Blade angle setting to be checked before and after test.

g) For tests 9c to 9f record fan speed,motor flow, ΔP, time, and position readout.

h) (Cyclic endurance test) endurance test for 50 cycles using cycle shown in table below:

Step	Blade Angle	Fan Speed
1	10^{o} Closed	2500
2	2^{o} Open	2500
3	2^{o} Open	3347
4	2^{o} Closed	3347
5	4^{o} Closed	3347
6	4^{o} Closed	3068
7	7^{o} Closed	3068
8	5^{o} Closed	3068
9	7^{o} Closed	3068
10	5^{o} Closed	3068
11	7^{o} Closed	3068
12	116^{o}Open	3068
13	116^{o}Open	2500
14	10^{o} Closed	2500

* For each cycle repeat steps 8 through 11 for 20 times.

Log sheet entries are to be made for the first and every 5th cycle thereafter. Maximum hydraulic supply pressure to be 3450 ±50 psig. The cycle frequency will be determine at the time of test.

IV) Test set up and instrumentation

1) Parts to be tested are to be mounted into test rig defined by 4013213-145

2) During all testing except initial manual checkout an oil flow is to be provided. The oil is to be supplied at port described in view EE zone D11 on drawing 4013213-140.

Type Oil -------------------- MIL-L-23699
Lube Flow -------------------- .75 - .80 gpm
Lube Pressure ---------------- 44 - 46 psi
Temperature ------------------ 120 - 140°F
Filtered to 10μ or less

3) A slave hydraulic system is to be provided including the following

a) A hydraulic pump having a capacity of 0-20 gpm and 3450 psi. Fluid used to be MIL-L-23699.

b) Filtration level to be 10 miron or better.

c) A servo valve to control flow into and out of motor shall be provided.

d) Polarity of hydraulic lines should meet the requirements of 4013151-994P01.

e) Flow meter, pressure and temperature taps to be provided.

f) A flow restrictor manually adjustable between 0-20 gpm up stream of servo valve to be provided.

4) The hardware to be tested contains position feed back composed of two mechanically driven LVDT's. Readout and excitation requirement for these LVDT's is to be provided. LVDT is defined on drawing 4013213-116.

5) The following instrumentation is to be provided:

	Panel	Sanborn
a) Fan Speed 0-4000 rpm	X	X
b) Hydraulic flow 0-20 gpm	X	X
c) Motor ΔP (Bi directional) 0-4000 psi	X	X
d) Motor pressure Port 1 0-4000 psi	X	X
e) Motor pressure Port 2 0-4000 psi	X	X
f) LVDT #1 ±.5 volts/volt excitation	X	X
g) LVDT #2 ±.5 volts/volt excitation	X	X
h) Lube oil pressure 0-75 psi	X	
i) Lube oil temperature 0-200 °F	X	
j) Hydraulic fluid temperature 0-250 °F	X	
k) Hydraulic fluid supply pressure 0-4000 psi	X	
l) Vibration meter	X	
m) EHV current ±100 ma	X	X

6) Photographs of test stand and test hardware to be provided.

VI) References

1) Figure 1.0 showing predicted fan blade twisting torque versus blade angle setting.

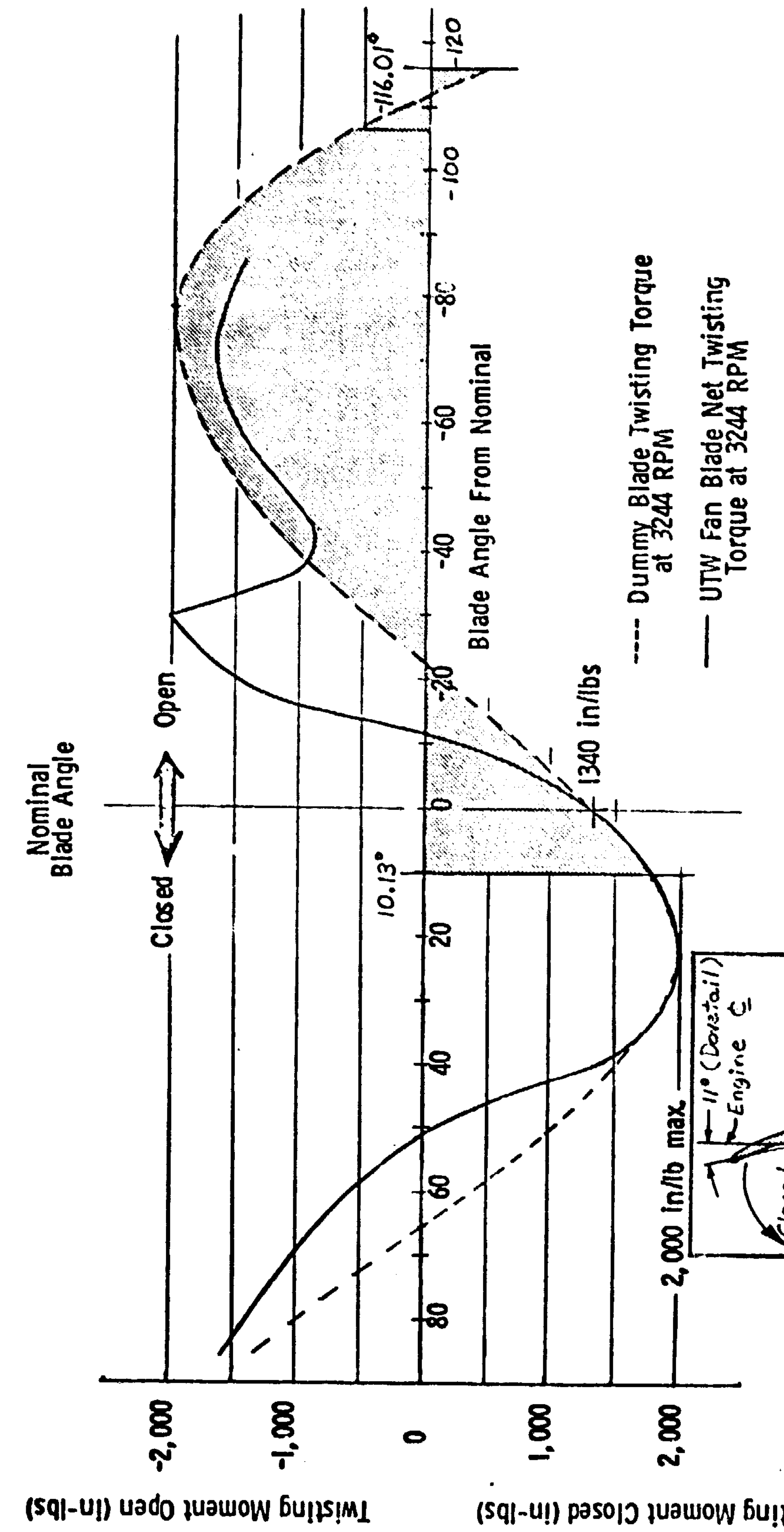
2) Figure 2.0 showing estimated motor flow versus speed.

3) Figure 3.0 showing estimated motor torque versus speed at various differential pressures.

4) Figure 4.0 showing hydraulic system schematic.

5) Figure 5.0 showing system schematic when using "bread board" control.

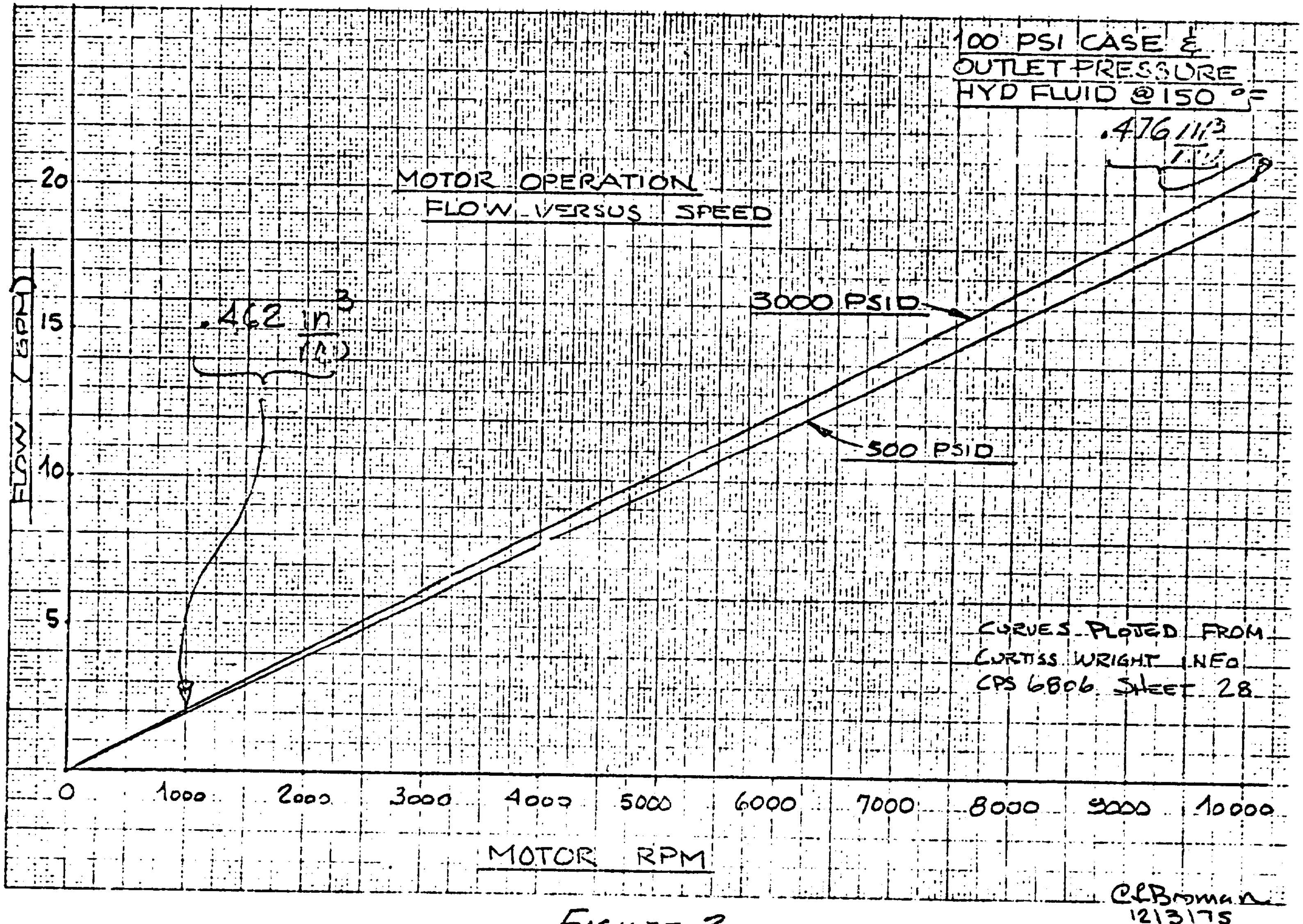
Fan Blade Twisting Torque — G.E. QCSEE Whirligig



Twisting Moment at other speeds

$$M_x = \left[\frac{N_x}{3244}\right]^2 \times M_{@3244\ \text{rpm}}$$

Figure 1.0



MOTOR OPERATION
FLOW VERSUS SPEED
100 PSI CASE &
OUTLET PRESSURE
HYD FLUID @150 °F
.476 in³
.462 in³
3000 PSID
500 PSID
CURVES PLOTED FROM
CURTISS WRIGHT
CPS 6806 SHEET 28
FLOW (GPM)
20
15
10
5
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
MOTOR RPM
C.L.Broman
12/3/75

FIGURE 2.0

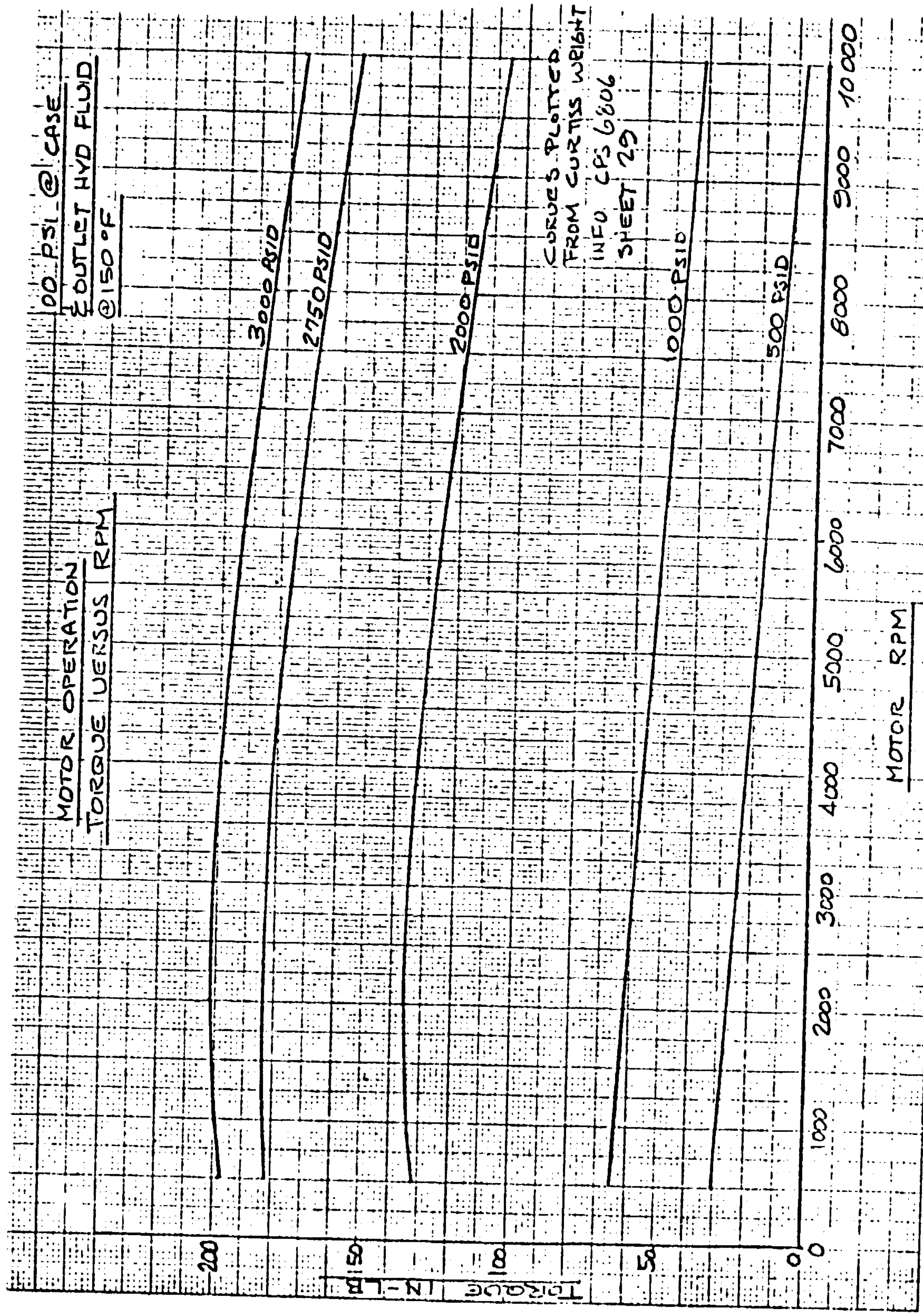
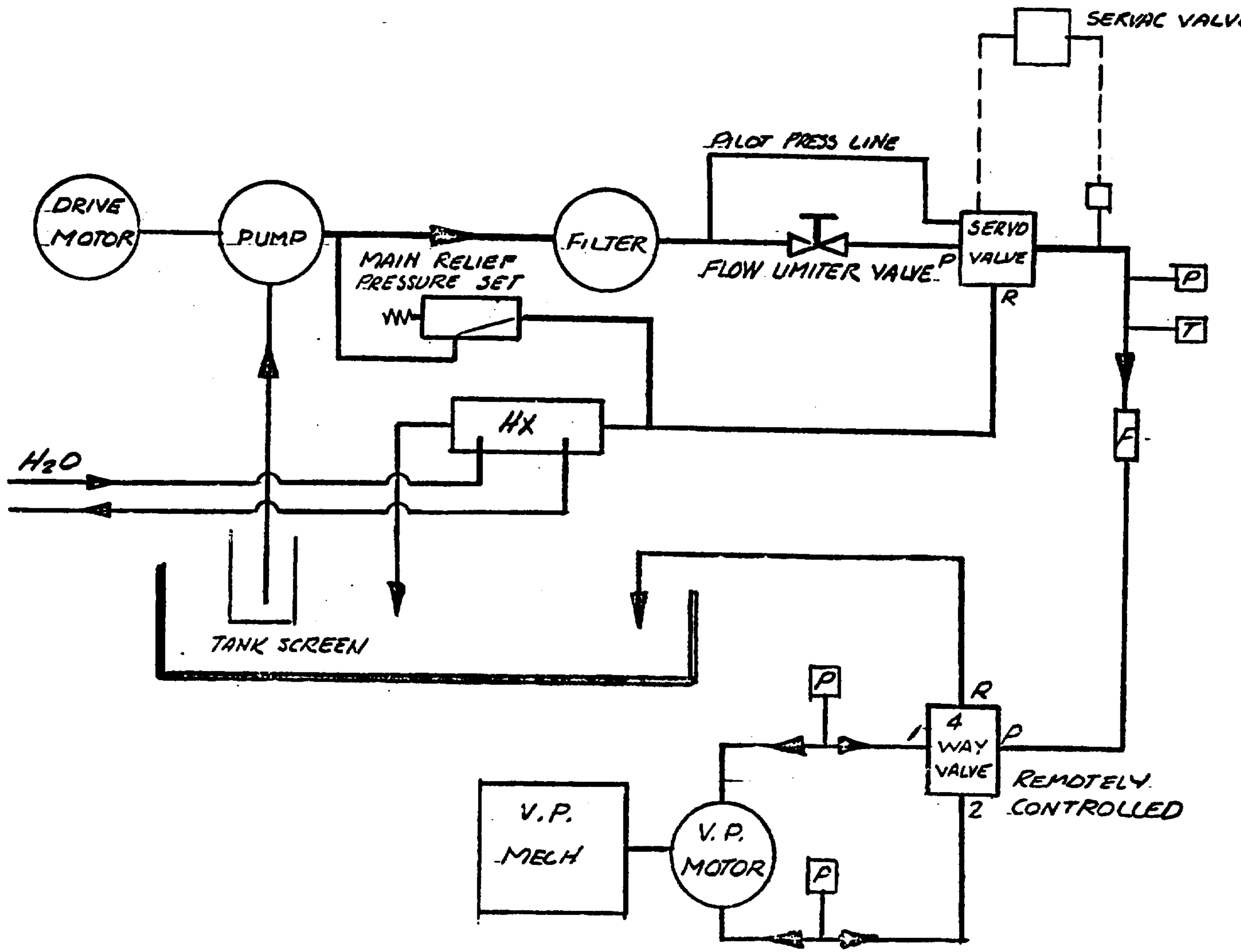


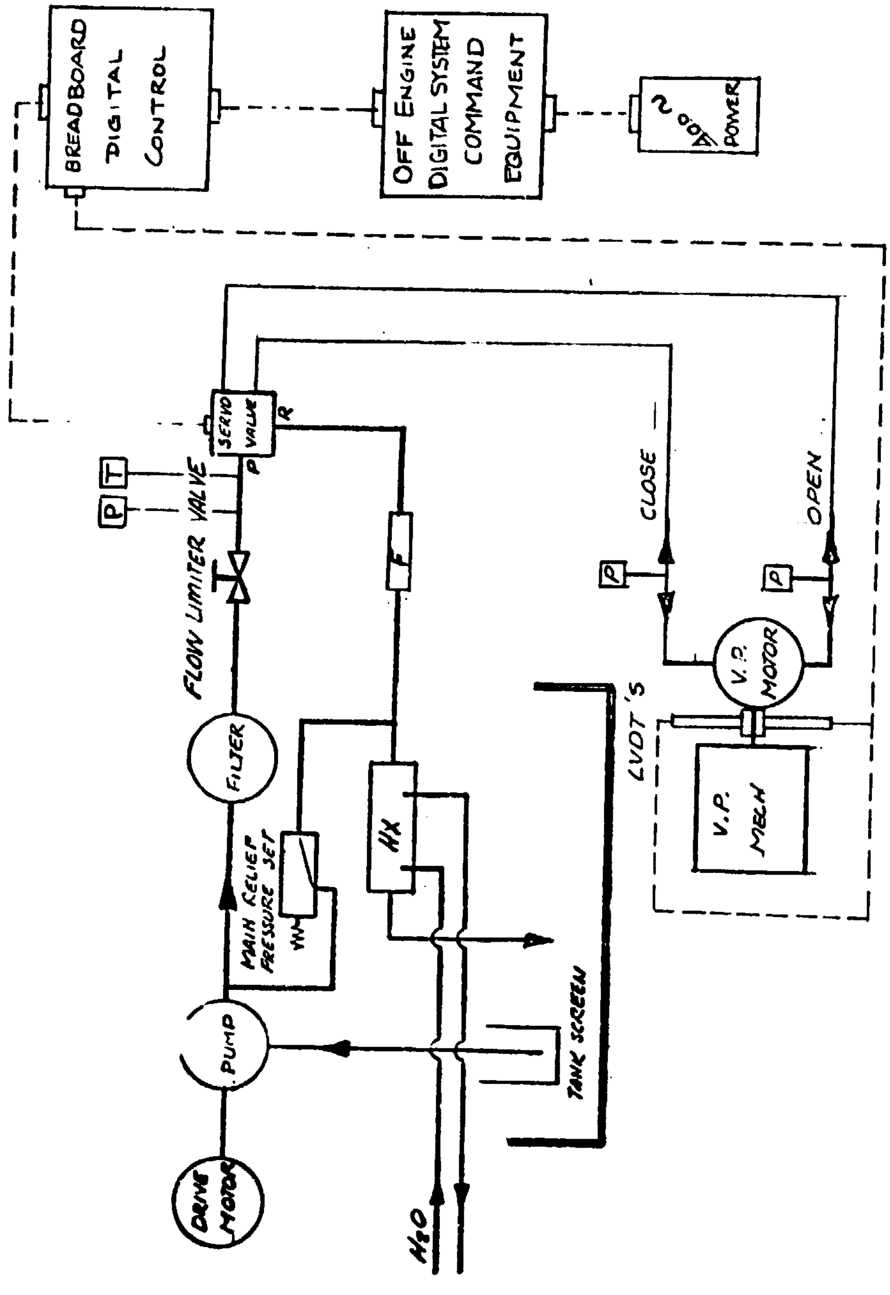
FIGURE 3.0

C.L.Bromon 12/3/75



SLAVE HYDRAULIC SYSTEM SCHEMATIC

FIGURE 4.D



SYSTEM SCHEMATIC
USING "BREAD BOARD" DIGITAL CONTROL

FIGURE 5.0